Tampereen yliopisto

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MATERIAL OPTIONS TO REPLACE GLASS FIBRE REINFORCED POLYMER COMPOSITE IN REMOTE FREEZER

Faculty of Engineering and Natural Sciences
Master thesis work
January 2020

ABSTRACT

Anniina Tossavainen: Material options to replace glass fibre reinforced polymer composite in remote freezer

Master thesis work

Tampere University

Material Science

January 2020

Glass fibre reinforced polymer (GFRP) composites are used as base materials in remote freezers. GFRP has many disadvantages such as poor recyclability and harmfulness for peoples' health. In addition, it has poor dimensional stability due to relatively high thermal expansion and uneven quality in manufacturing. The aim of this thesis is to find material solution which removes mentioned disadvantages and offers better properties.

Finding new material options began with defining the key features of the freezer base which are among other things corrosion resistance, surface quality, dimensional stability, strength, hardness, wear resistance, thermal conductivity and formability. After determining these properties, a large number of materials were screened to fulfil the properties at a sufficient level. GFRP was used as a reference, but the comparison was difficult due to lack of experimental test data of the current material. By using material selection charts and comparing technical properties, the most optimal materials for testing were chosen. Availability of materials changed original test material plan but ordered materials were close to original selections. A few test materials were ordered because they were suggestions from supplier. Test methods were selected to measure as well as possible the required key properties.

Test results were compared with each other and GFRP. Based on the test results and analyzation, new material options and future prospects of the research are presented in conclusions.

Keywords: glass fibre reinforced polymer composite, base materials of freezers, chemical resistance, mechanical properties, material selection process, material testing

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Anniina Tossavainen: Materiaalivaihtoehdot lasikuituvahvisteisen polymeerikomposiitin korvaamiseksi keskuskoneellisissa pakastimissa
Diplomityö
Tampereen yliopisto
Materiaalitekniikka
Tammikuu 2020

Lasikuituvahvisteisia polymeerikomposiitteja käytetään pohjamateriaaleina pakastinkalusteissa. Lasikuituvahvisteisella komposiitilla on paljon huonoja puolia, kuten heikko kierrätettävyys ja haitallisuus ihmisten terveydelle. Lisäksi, sillä on heikko mittapysyvyys johtuen suuresta lämpölaajenemisesta ja valmistuksen epätasaisesta laadusta. Tämän työn tavoitteena on löytää materiaaliratkaisu, joka poistaa mainitut ongelmat ja tuo lisää etuja käyttökohteeseen.

Uusien materiaalien etsiminen alkoi määrittelemällä pakastimen pohjan tärkeimmät ominaisuudet, joita ovat muun muassa korroosion kestävyys, pinnan laatu, mittapysyvyys, vahvuus, kovuus, kulutuksen kesto, lämmön johtavuus ja muovattavuus. Määrittelyn jälkeen suuri määrä materiaaleja suodatettiin, jotta löydettäisiin materiaalit, jotka täyttävät vaatimukset riittävällä tasolla. Nykyistä materiaalia käytettiin referenssimateriaalina, mutta vertailu oli vaikeaa johtuen siitä, ettei nykyisestä materiaalista ollut olemassa kokeellista testausdataa. Materiaalinvalintakuvaajia käyttämällä sekä teknisiä ominaisuuksia vertailemalla valittiin kaikista optimaalisimmat materiaalit testaukseen. Materiaalien saatavuus muutti alkuperäistä testimateriaalisuunnitelmaa, mutta tilatut materiaalit olivat lähellä alkuperäisiä valintoja. Muutamia testimateriaaleja tilattiin toimittajien suosituksesta. Testimenetelmät valittiin mittaamaan niin hyvin kuin mahdollista vaadittuja ominaisuuksia.

Testituloksia vertailtiin keskenään ja lasikuituvahvisteisen komposiitin kanssa. Perustuen testituloksiin ja analyysiin, uudet materiaalivaihtoehdot esitetään loppupäätelmissä ja mitä tulevaisuuden näkymiä tutkimuksella on.

Avainsanat: lasikuituvahvisteinen polymeerikomposiitti, pakastimen pohjamateriaalit, kemikaalien kesto, mekaaniset ominaisuudet, materiaalinvalintaprosessi, materiaalitestaus

PREFACE

This Master's thesis has been carried out in collaboration with Viessmann Refrigeration Systems Oy, in Porvoo in 2019. The work is done in new product development team for new freezer platform project.

I would like to thank Viessmann for the good cooperation, especially my supervisor Lassi Nieminen and the laboratory team, which made fruition of my project possible. In addition, I would like to thank my supervisor from university, Essi Sarlin, for her excellent guidance even in challenging questions. Suppliers I would like to thank for are Aikolon, Alumeco, SSAB, Pinnoitus-Helin and Pettersteel, which delivered my test samples for my project. I also thank for my associates for their support and faith in my work. Tampere University has provided very good start to working life and the future.

Porvoo, 9.12.2019

Anniina Tossavainen

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LIST OF TERMS (SYMBOLS AND ABBREVIATIONS)

GFRP = Glass fiber-reinforced plastic

3D = Three-dimensional

SEM = Scanning Electron Microscopy

ABS = Acrylonitrile-butadiene-styrene

ISO = International Organization for Standardization

POM = Polyoxymethylene

UV-radiation = Ultraviolet radiation

PE = Polyethylene

LDPE = Low-density polyethylene

HDPE = High-density polyethylene

UHMW = Ultra-high-molecular-weight

FDA = Food and drug administration

F = As manufactured

O = Annealed

H = Strain-hardened

W = Solution heat treated

T = Heat treated to obtain stable tempers

NaCl = Sodium chloride

ASTM = American Society for Testing and Materials

NaOH = Sodium hydroxide

1. INTRODUCTION

Glass fibre reinforced polymer (GFRP) composite is used in remote freezers as a base material. The aim of this thesis is to replace GFRP, because it is not a cost-effective solution, it is harmful for peoples' health, slow and inaccurate to manufacture, really difficult to recycle, the material solution is not optimized for the application and its specs are exaggerated. Also, the reasons why it was chosen in the past are many. It is resistant to temperature fluctuations, with good corrosion and chemical resistance, good surface quality due to gel coat and it has very good mechanical properties, yet it is very lightweight. Thus, this thesis is done to maintain these good qualities while eliminating disadvantages.

In addition to the good features of GFRP, it is important to consider which features are important in this particular application because GFRP is not optimized solution. Properties must take into account requirements during manufacture and use because manufacturing process has higher temperatures than usage. Once the important properties have been selected, it can be started to go through materials in different tables and material selection charts and evaluate the adequacy of their properties. GFRP is used as a reference as far it is possible, because there is no numerical data available before testing, so the test material selection is difficult. The selection process is also influenced by availability and price, so interacting with material suppliers is a big part of the process. Deciding the size and the number of test pieces and ordering the pieces is based on the tests that are performed. When designing tests, it is considered which tests are the best to measure the features that are considered important.

After the tests, analysis of the results using GFRP as a reference begins. Analysis includes evaluation of the reliability of the tests, possibility for errors and answering the question: are the results comparable. Various tools can be used to score properties and materials, thus facilitating the processing of results.

2. CURRENT GFRP-STRUCTURE

Glass fibre reinforced polymer (GFRP) composite consists of glass fibre mat and resin. The current material is staple fibre composite, where the fibres are short and not in certain order. The thickness of the mat and fibre orientation define the rigidity of the structure. Resin is liquid which is mixed with hardener and after that pressed between the fibres by brush. Fibres are glued with resin to their form which is called lamination. There are a lot of lamination techniques and the one described above is just one of them. The final piece is called laminate. (1)

GFRP base of remote freezer is manufactured by hand lay-up process, also known as wet lay-up. It is the oldest method to manufacture composite parts in industry. Fibres are arranged in certain directions depending on the performance demands of the material. Before lamination the mold has to be cleaned properly with warm water and detergent. After cleaning, gel coat of resin and curing additives are applied on the surface of the mold. Gel coat is used to do the surface finish for resin and it also protects the laminate structure from water and mechanical impacts. Most common gel coating materials are thermosetting polymers based on epoxy or unsaturated polyester resin chemistry. Possible top coat acts as surface painting. Gel coat is applied by sprayer or brush. Circumstances have to be dustless and temperature range must be uniform. (2)(3)

There are many reasons why GFRP has been selected as the base material. The conditions are challenging during manufacturing and use in freezer. Polyurethane foam acts as the main heat insulator in the structure, so the base material does not have to be heat insulating in nature even though GFRP is. In the urethane casting, polyurethane polymers are formed by *di*- or *tri*-isocyanate and polyol reaction. During casting, the temperature rises to 52 °C and the pressure at which urethane injection occurs is 120-130 bar. GFRP sustains these fluctuations in temperature and pressure well. During usage, the temperature range is approximately 50 °C. During defrosting, the temperature rises to room temperature, which depends on the environment (assumed 25 °C). During cooling, the coldest parts of the freezer are up to -25 °C. The freezer creates a corrosive environment during defrosting as the defrost water flows down the drain. To keep the base clean, the surface must be smooth and resistant to mild deter-

gents. GFRP has corrosion and chemical resistance for these processes. An evaporator is placed on the base (**Figure 1**), which, when vibrated, causes stress on the base material. The material on the other side of the cast frame is a sheet metal, which sets a requirement for the thermal expansion of the replacement material to prevent the bottom structure from twisting. The endurance of these stresses is indicative of the mechanical and thermal properties of GFRP.

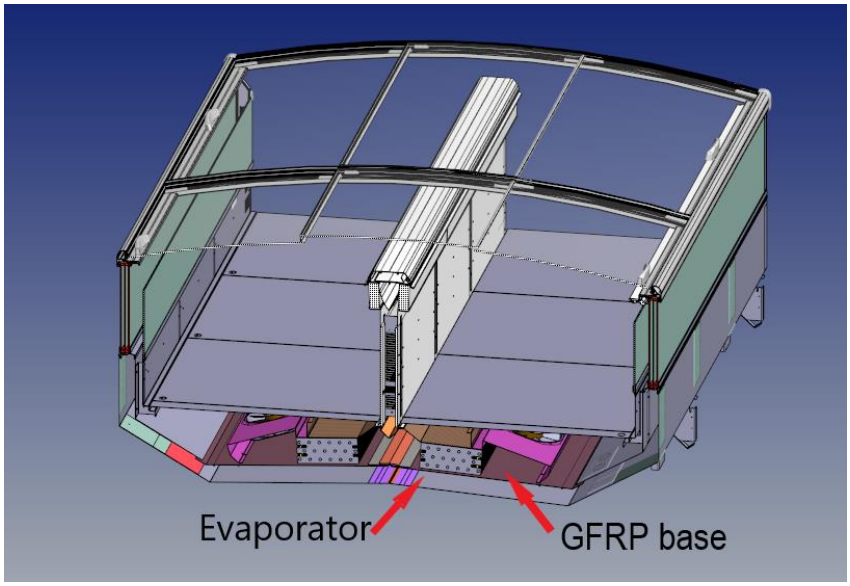

Figure 1. *3D model of the freezer.*

GFRP is well adapted to the prevailing conditions, but it has its own disadvantages. Raw materials of GFRP are more expensive than metals, but GFRP is lighter material (4). However, polymers and aluminum alloys are also relatively lightweight materials. Laminating is dangerous for workers because the styrene in the matrix is volatile and has been shown to cause brain disease to boat manufacturers and in addition styrene is also examined to cause skin irritation and there is limit for injurious inhaling which is 400 ppm (5). Hand lay-up method is relatively slow with long drying times and it also requires skills from the processor (6). Due to handmade fabrication, the finished GFRP-bases exhibit inaccurate measurements which make it difficult to fit the bases into the casting body. This uneven production together with high thermal expansion compared to metals is referred to a term “unstable dimensions”. Recycling is also problematic with GFRP. For example, aluminum can be nearly 100% recycled, but recycling rate of GFRP is very low, even non-existent. Advantages and disadvantages are summarized in **Figure 2**.

Glass Fibre Reinforced Polymer

Advantages	Disadvantages
Resistance to temperature fluctuations	Non-cost-effective
Corrosion/chemical resistance	Harmfulness
Surface quality	Hand lay-up manufacturing
Mechanical properties	Unstable dimensions
Lightweight	Poor recyclability
	Not optimized
	Exaggerated specs

Figure 2. *Advantages and disadvantages of GFRP.*

The material selection process began by examining the critical properties of the application and using GFRP as a reference. Replacing material has to include the advantages of GFRP but also to be as ideal as possible to the environment and application. GFRP base is not an optimal solution for a base material in freezer cabinets because its specs are exaggerated. The starting point is to understand the factors behind the advanced properties of GFRP. After the sources of properties are understood it is easier to find new material solutions. In order to find a new alternative material to GFRP as a substitute, one must utilize material selection processes.

3. THEORY BEHIND MATERIAL SELECTION

The material selection process starts with mapping the circumstances and structure of the product (7). The materials used in boat industry are very similar to those in the freezer base. A huge amount of boat structures include glass fibre reinforced polymer composite (GFRP) structure. The conditions in freezer cabinets are in fact very similar to marine environment in Finland. Boats have to sustain temperature variation between -30-+30 °C, depending on the season. Therefore, it is a good perspective to look into materials that are used in boat industry.

In this thesis various composites, metals, polymers and coatings including surface modifications have been extensively studied. Materials available for testing have been highlighted in the text, but other rejected options are listed in APPENDIX A. There are also materials selection charts (APPENDIX B), which offer rough estimate of properties and help to narrow the choice of candidate materials. This chapter will walk you through the general material selection process that will provide case-by-case review of the desired material properties in the next chapter.

3.1 Design

The selection of material for the application starts with the design of the product. The material selection process is a systematic one that proceeds step by step towards the desired direction. The research question is divided into several levels, which are addressed by different engineering design tools.

At first, there are large number of options to choose from; all the materials of the world. In some cases, you have one strict technical demand from the material, and it is easy to eliminate some groups of materials based on that, e.g. selection of window material has one demand above other: opacity has to be near zero which leaves only glass materials and transparent plastic materials (8). In this application, such a key factor is the corrosion resistance, but the alternatives are not so simple due to the different possibilities to improve the corrosion resistance of the materials.

As you study product design and the criteria are met, the range of alternatives is radically reduced. More detailed information and data are needed to ultimately limit the number of options to a few or even just one. On the other hand, the end result may also be that there is no better material alternative for the product, at least with the current design. The material selection influences not only to the product itself but also to the surrounding world. The five key factors when designing a product are market, technology, investment climate, the environment and industrial design. New innovations in materials and technology should be taken into account in the design, also considering sustainability. The design process is visualized in **Figure 3**. (7)(9)

The outcome of many design processes remains open. The process rarely provides to a definite and correct solution, but is able to present certain solutions to be better than others. Therefore, it is important that the designer is open-minded and ready to see even surprising alternatives as potential. (9)

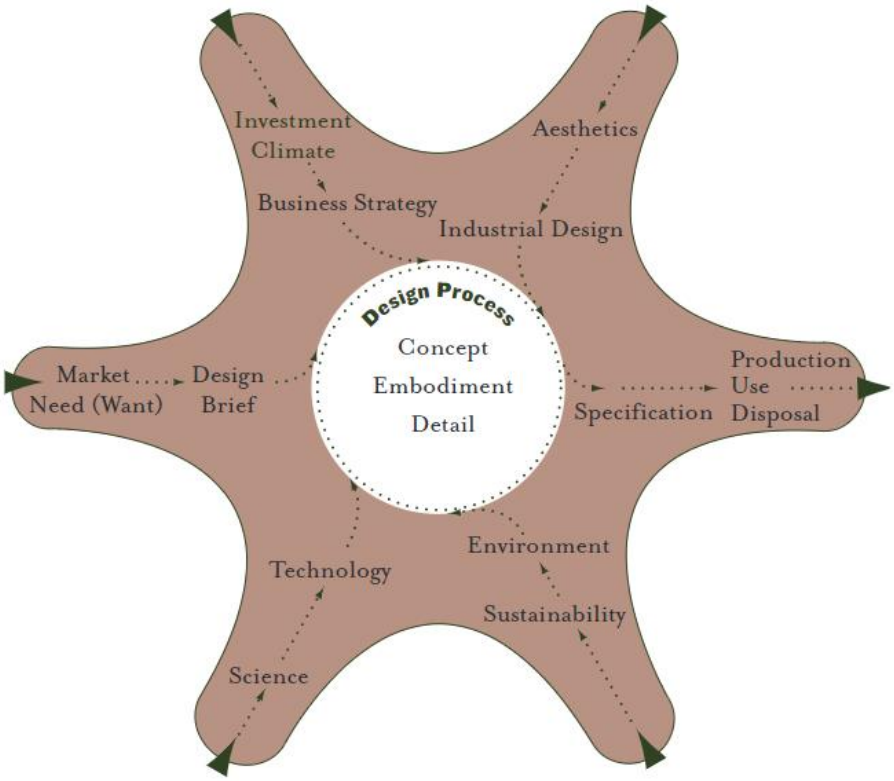

Figure 3. *Inputs to the design process (7).*

Figure 4 shows the features and functions of new technologies, materials, processes and products. As in **Figure 4** is presented, new solutions are generally expected to be

composites and have new structures and functions. As with this application, the new solution is expected to perform well and fulfil determined requirements, and often composites are good at combining the best of two or more different materials. The current solution is already composite and therefore new solution is not automatically better by selecting some composite. New processes comprehend shaping, joining and surfacing but in this application uniform structure is desirable. Reducing seams to prevent urethane leakage would be advantageous to the product, so the new material solution can provide better functionality and reduce the number of intermediate steps where seams need to be blocked. GFRP is not ideal for the environment, so smaller environmental impacts can be achieved with the new solution, so some typical expected functions of new products fulfil. There is no need to improve the visual aspect, so it can be maintained at the same level or improved. In next section are considered factors in a large scale influencing material selection. (7)

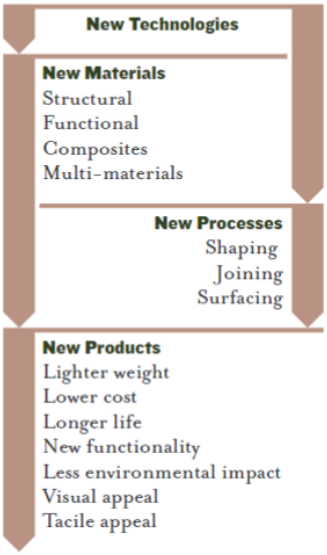

Figure 4. *New technologies, materials, processes and products (7).*

3.2 Factors influencing material selection

The factors that influence the choice of material can be divided into four categories:

- costs,
- requirements for desired functions,
- requirements for the environment and
- requirements for the manufacturing process.

These factors form a whole that takes into account the properties of the material and its suitability for the application on a large scale. This thesis work takes into account re-

quirements for desired functions and environment but costs and manufacturing processes have smaller importance because economic matters change during time and manufacturing process can be totally different if the structure is redesigned. (10)

Costs consist not only of the cost of manufacturing/purchasing but accounts for the total cost over a lifetime; the so-called life-cycle costs. Total cost is presented in **Figure 5** and includes material acquisition costs, manufacturing costs, in-service costs, quality control costs, administrative costs and disposal costs. When selecting a material, all these costs must be taken into account in order to get an honest estimate of what the cost of choosing a new material is compared to the previous one. Costs are incurred before the actual purchase and manufacture of the product materials. Expenses include product development, design and implementation of test arrangements, and the purchase of test materials and sample preparation. (10)

In order to know the requirements of the desired functions, one has to consider what these functions are, as described in chapter 4 (10). For example, structure must remain load-bearing during casting in order to perform the polyurethane molding, which requires: sufficient rigidity and hardness. Another example is the base cleaning: it requires a certain surface quality: dirt repellent, non-porous and non-absorbing surface.

Operating environment requirements include temperature range, barometric pressure, chemical and mechanical stress (10). For example, the freezer design is such that the die faces of the die base are at different temperatures. Then the thermal expansion coefficients for different materials must be taken into account. Other environmental stresses include the corrosive environment during thawing, the location of the evaporator on the base and resulting vibration and wear caused by the possible loading of the goods.

The requirements of the manufacturing process include the suitability of the material to be modified as required by the method. For example, not all metals are suitable for cold working and others are not suitable for heat treating. For instance, the typical sheet processing methods of polymers are heat and vacuum forming and generally speaking, engineering polymers are not possible to work with them due to spring-back effect. However, manufacturing methods will vary if the structure is redesigned. The following section describes how the test materials are selected.

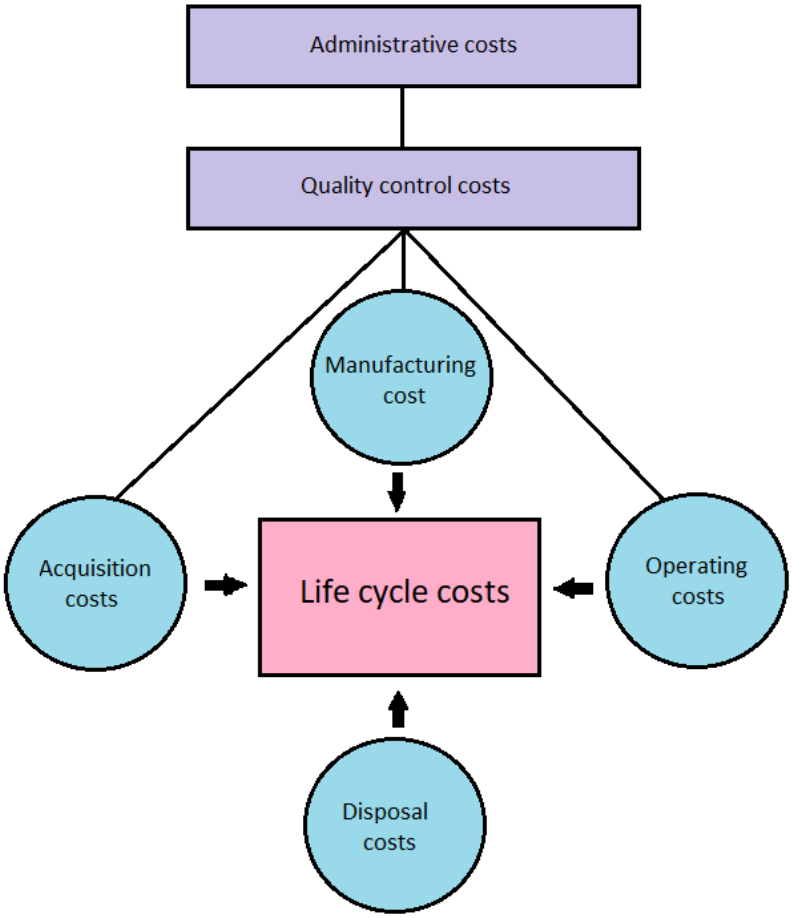

Figure 5. *Life cycle costs (10).*

3.3 Steps of material selection

The choice of material is based on technical factors and it is important to consider the required features of the product, as discussed in chapter 3.2. With all materials being alternatives, their suitability to replace the current solution was investigated through material charts and technical data sheets. The rough description of procedure of material selection is presented in **Figure 6**. Before researching the material selection charts, it was necessary to identify and prioritize the critical properties. A critical property means that if the critical property has a poor value, the material is automatically rejected. These properties are introduced in chapter 4. Literature values of GFRP are used as a reference for estimating the value. It is, however, almost impossible to determine the correct limit for certain properties without testing, since the properties of GFRP may be exaggerated for the application.

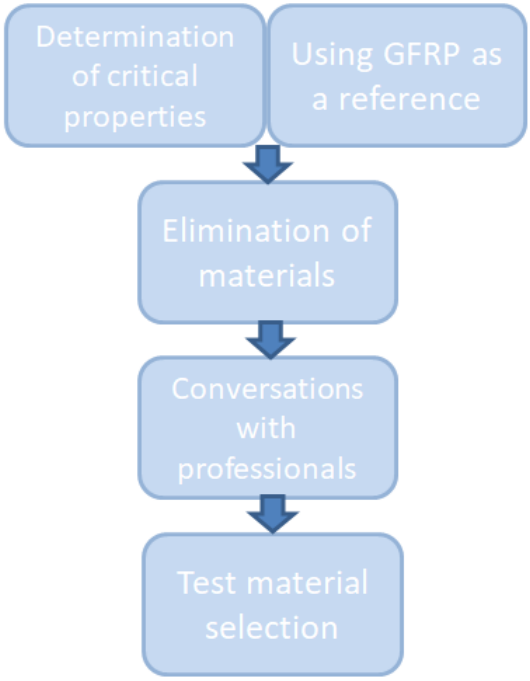

Figure 6. *Procedure of test material selection.*

In the material selection charts, materials are divided into polymers, metals, composites, elastomers, foams, technical and non-technical ceramics. “Technical Design” of **Figure 7** illustrates how material options are reduced when considering the effects of mechanical, thermal and other technical aspects. The properties of the materials can be divided into quantitative and qualitative properties. Quantitative properties are amongst other things density, Young’s modulus, tensile strength, elongation at break, fracture toughness and hardness. Qualitative properties are corrosion resistance, surface protection/quality, chemical resistance and environmental impact. The latter are more difficult to evaluate and compare without testing. They are also identified in the later section as the most important features and therefore tests are essential for selection. (7)

In the end, product design and feasibility reduce the options even further, and eventually researching prototypes, 3D-models or the like limits the options to a few. Important information on material selection is available directly from a supplier who has specific information on materials and an estimate of the most appropriate material for the application. To ensure the correct choice of material for the critical component, tests are first performed on the specimens, after which the prototype is shown to be genuine suitability for all parties. Price and availability are often the last attributes to help to make the final decision. (7)

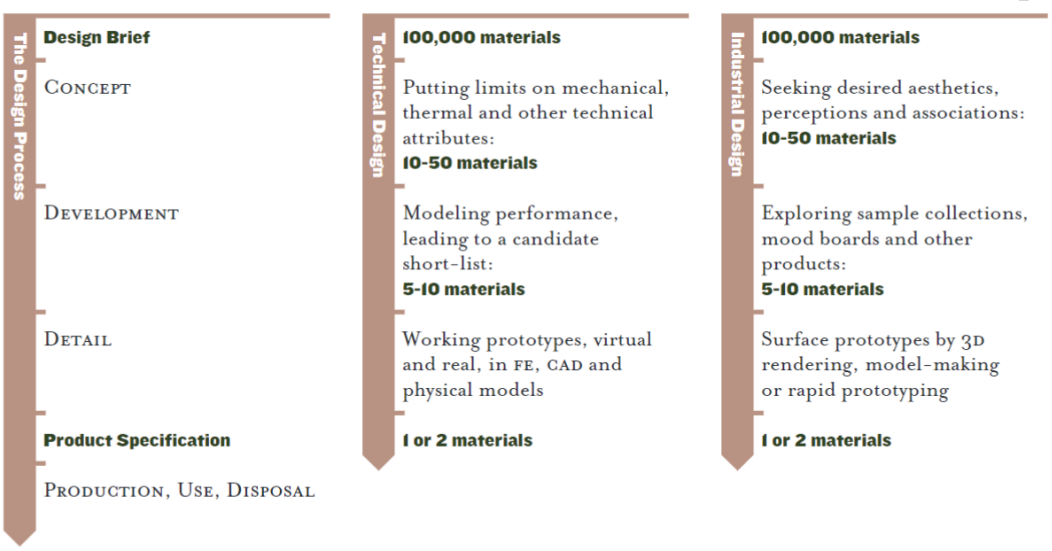

Figure 7. *Materials in design process (7).*

4. IMPORTANT MATERIAL PROPERTIES FOR THE APPLICATION

In this chapter, the most important material properties for the application are determined and properties of GFRP are used for comparison. The main properties are listed below:

- Corrosion resistance
    - Durability of variations in pH
- Surface quality
- Dimensional stability
    - Water absorption
    - Thermal expansion
- Toughness and rigidity
- Hardness
- Wear resistance
- Thermal conductivity
- Formability.

GFRP composite is used a lot in technical applications, such as in boat industry, due to its mechanical properties, lightweight, chemical and corrosion resistance, as discussed in chapter 2. Beneficial properties are also relatively low thermal expansion and high energy absorption capacity in comparison to materials that have similar density. Additives are used in GFRP to decrease the cost of the material also enhance certain properties, such as workability. (1)(3)

4.1 Corrosion resistance

Chemical degradation of a material is called corrosion. Factors predisposing to corrosion occur in the environment: humidity and contaminants. Changes in temperature and pressure can accelerate corrosion. Corrosion is avoided by designing, material selection, controlling the conditions and measuring the corrosion rate correctly. (8)

Corrosion resistance is one of the most important material properties which determine the material selection. It is important because moisture can condense on the structure

in melting process and if packages of groceries got broken there would be a possibility for galvanic corrosion. Galvanic corrosion is possible due to the presence of various metals such as stainless steel and sheet metal in the structure. (8)

Especially corrosive substances are CO_2, H_2S and Cl^-. If these three components are combined there can occur several corrosion problems, even in GFRP-structure. Carbon dioxide is used as a protective gas in groceries. Frozen fish can include bacteria that produce hydrogen sulfide. It is seen that fibres are prone to corrosion rather than resin but if the resin is damaged it cannot protect the fibres and corrosion is accelerated. Acid concentration is kept as a key factor when corrosion occurs in glass fibres but also associated anion can form complex ions which lead to corrosion. Corrosive factors are also salt solutions, different carbon dioxide partial pressure and hydrogen sulfide pressure. Carbon dioxide and hydrogen sulfide are capable of dissolving in water and participate in the formation of carbonic and hydro sulfuric acid. (11)

In this application there is also gel coat, as mentioned, which protects the glass fibres from corrosion with the help of epoxy matrix. When considering composite materials as the solution to replace current material, some kind of coating is needed to protect reinforcement material, because it is impossible to fully cover it by matrix.

4.1.1 Durability of variations in pH

The chemical nature of the electrolyte is important in corrosion behavior, and in particular its pH-value. Pourbaix-equilibrium diagrams are used to evaluate pH-value. Diagrams show the potential of metal to be oxidized, which means the same as active. When metal is passive it is protected against corrosion. The pH varies as a result of chemical reaction, a change in concentration, or stagnation in the crevices. Metals can be divided into three groups depending on how much pH affects their corrosion behavior: noble, amphoteric and industrially important metals. Noble metals do not react to pH changes, amphoteric metals do not react in neutral range and industrially important metals only in exceptions, for example in case when there are strong alkalis on iron. Aluminum belongs to amphoteric metals and steel to industrially important metals. (8)

Base material has to sustain mild (pH 6-8), non-toxic detergent which is used to clean the freezer. Solvent-based detergents are not allowed to use. Another chemical load comes from groceries if packages fail. Base material has to endure salty liquids and other runoffs from groceries.

4.2 Surface quality

Surface quality has to be considered precisely from both sides of the base plate. Downward surface is prone to polyurethane and upper surface is under base covers (**Figure 8**). The upward surface of GFRP is coated by gel-coat and the downward is pure composite material but the adhesion to polyurethane is ensured by sand layer.

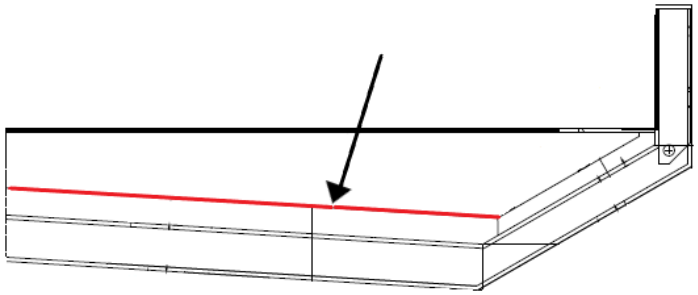

Figure 8. *Cross-sectional view of the tank freezer, structure of the base. Red line refers to the place of GFRP base.*

Adhesion between polyurethane and base material of a remote freezer is a very important factor in the structure of the freezer. In general, adhesion of metals to urethane is inherently good, so the steel surface underneath is easily attached to urethane. With GFRP the adhesion is poor and therefore in laminate manufacture there is added sand so that the urethane will seize into laminate. When considering materials to replace GFRP it is essential to consider adhesion and understand the reasons behind it.

Polyurethane is formed of two components, polyisocyanate and polyol, via chemical reaction. The bonding between substances is strong and essential for material's performance. Surface properties of urethanes are crucial in the matter of adhesion. Composition has a strong effect on adhesion but also physico-chemical factors and their contribution, especially surface properties are fundamental. (12)

4.2.1 Hardness

Hardness is an important property in aesthetical point of view. Hardness can be expressed as ability to resist plastic deformation which is usually done by penetration. Hardness describes also the ability to resist scratching. There are several test methods to execute hardness tests and their general principle is to measure the dimensions of intender that has pressed a mark on the surface of the material. Hardness has a direct correlation with strength, wear resistance and other properties. It is one good reason to carry out hardness measurement for the material because a single test arrangement provides relatively large amounts of information on the mechanical properties of the material. (15)(16)

Hardness is an important property, because if the material does not have good enough resistance for plastic deformation, it is more likely to be scratched. Hardness can be increased by coating or surface treatment. The hardness of the current material is not known, but the GFRP is coated with a gel coat which makes the surface harder and more durable. The purpose of gel-coat is to provide a resin-rich surface with good surface quality and chemical resistance. Gel-coat contains color pigment on the product surface. (18)

4.3 Dimensional stability

Dimensional stability means that the dimensions of the product remain constant even though the temperature varies and it is strongly related to the thermal expansion properties of the material. From a design point of view, it is good that the thermal expansion is as small as possible so that, e.g., no distortion occurs in the structure. On the other hand, dimensional stability also means that the similar material components are the same size without significant variation. This means that quality of manufacturing is beneficial to be uniform. Dimensions may also change due to swelling if the surface quality is not good enough under humid conditions. Thus, water absorption properties have an effect on dimensional stability.

Dimensional stability is the thing to be pursed even though it is not excellent with GFRP either. Handicraft nature is seen because different laminates visibly vary among each other. The wide range of temperatures is a challenge with dimensional stability. Thermoset matrix was chosen as the current material because thermosets have better dimensional stability than thermoplastic materials. Thermosets are also nearly chemically

inert. The downside of thermosets is that they are more difficult to reuse or recycle. The epoxies curing time is quite long and a transformation may occur, e.g., distortions.

It is important that the base dimensions remain unchanged or nearly unchanged as the temperature changes, so that the base plate fits in with the other construction of the freezer. The reaction temperature of urethane during manufacturing (52°C) must also be considered when selecting the material.

4.3.1 Water absorption

Water absorption happens without chemical reaction but it can be considered either chemical or physical phenomenon. Water absorption is highly related with the contact angle of the solid and liquid material. When the contact angle is low the droplet spreads on the surface, whereas if the angle is high the surface repels the liquid. By knowing the contact angle it is possible to evaluate water absorption of the material. On the other hand, wettability is depended on surface roughness and thus surface roughness has impact on contact angle. Polymers with rough surfaces have low surface free energy and they can be super water-repellent materials. If the surface is flat, the water absorption is greater with the contact angle being smaller than the rough surface. Different treatments increase water repellent properties, e.g. oxygen plasma treatment. To characterize roughness features qualitatively, e.g. SEM is needed. In this thesis flat samples with smooth surfaces are used in water absorption test and contact angles are not determined. Thus, by selecting coarse enough surface, the final choice of material can prevent water absorption. (13)(14)

Water absorption is an undesired phenomenon and therefore high water absorptive materials are eliminated from the options. Water absorption causes swelling which affects dimensional measurements of the workpiece. Water absorption percent can be calculated with equation 1.

$$\%Absorption = \frac{Difference\ in\ weight}{Original\ weight} x\ 100 \quad (1)$$

4.3.2 Thermal expansion

Thermal expansion describes the change in surface area, volume and shape of a material as the temperature changes. Numerically, it can be represented by a thermal expansion coefficient which unit is K^{-1}. The thermal expansion coefficients can be used to calculate how much the length of a piece changes in temperature variation:

$$\Delta L = L \cdot \Delta T \cdot \alpha, \quad (2)$$

where ΔL is the change in dimension, L the original length, ΔT the temperature difference and α thermal expansion coefficient.

The coefficient of thermal expansion of the new material has to be similar to as the casting counterpart's. If the entire structure is of the same material, the difference in thermal expansion coefficients need not be taken into account. If material has fasteners, thermal expansion must be taken into account so that the fastening mechanism cannot break. It must also be avoided that the joint between the base and the wall material does not break and water does not come into contact with polyurethane.

On the other hand, different coefficients of thermal expansion can be taken into account in designing. Knowing the thermal expansion coefficient of material over a given temperature range, the magnitude of expansion can be estimated. For example, in this application, it would be safe to design the structure to withstand an expansion between -25 °C and 52 °C, a total of 77 °C. As discussed in chapter 2, the temperature is highest during urethane casting.

The different sided surfaces of the casting base are in different temperatures when freezer is on. Lower surface is approximately at 10 °C and upper -20 °C. The difference in temperature is therefore 30 °C, but can reach even 50 °C.

There are large differences in thermal expansion behavior between different groups of materials. In general, the thermal expansion of polymers is significantly higher than that of metals. There are also exceptions, such as ABS, which has a relatively low thermal expansion compared to other – even engineering plastics – and thus offers better dimensional accuracy. Regardless, GFRP has smaller thermal expansion coefficient than polymers.

4.4 Toughness, rigidity and impact strength

Toughness is a term that describes the ability of a material to absorb energy into a plastic region and can be represented by a stress-/strain-curve. It can also be defined as the ability of deformed material to resist fracture, i.e., the amount of energy per volume to be absorbed in the plastic region prior to fracture. Toughness and strength are often mixed together, but they do not mean the same thing, especially when dealing with brittle and tough materials. The difference is as follows; strength refers to how much force a material can withstand before fracture, while toughness describes how

much energy a material absorbs before fracture. Brittle materials have high strength but are not tough because of their limited strain value. Toughness can thus be summed up as a combination of strength and ductility. Ductility in turn means ability to sustain deformation without fracture. (15)(16)

Rigidity is essential in assembly step. The GFRP profiles are at the maximum 3.5 meter long and they have to be rigid enough so that they do not warp when collector is transferring it. Depending on material, rigidity can be enhanced by the thickness of material sheet. If the material is flexible by nature thicker sheets are required to fulfil rigidity demands. In crystalline materials like metals, rigidity is originated from strength and strength is affected by dislocation movement in crystals (15). Rigidity of amorphous materials, like polymers, is depended on glass transition temperature. Above it, rigidity decreases significantly. (17)

Impact strength describes ability to resist mechanical shock without failure and it is important because in -20 °C the behavior of materials is more brittle with polymers, although depends on glass transition temperatures. The ductile/brittle –behavior of polymers can be measured according to ISO 6603-2. For polymers, the glass transition temperature is particularly important because, at this point, the behavior changes from ductile to brittle as the temperature decreases. Table of glass transition temperatures of selected test polymers are presented in chapter 5. Brittle nature at lower temperatures is due to a reduction in molecular chain motion. For amorphous polymers, a change in ductile/brittle –behavior is observed near the glass transition temperature. Other things that affect ductile/brittle –behavior are chemical contact, degradation, contamination, strain rate, etc. The glass transition temperature of GFRP depends on the matrix and the proportion of the fibres relative to the matrix. (16)(17)

4.5 Wear resistance

Wear is movement that is resisted by friction between two different surfaces and friction can be reduced by lubricant. Wear can cause mechanical failure as a result of structural weakening. Good enough wear resistance is important, because vaporizer is located on the base plate and it causes vibration movement. Vibration is caused by operation of vaporizer but also thermal expansion of compressor and copper pipes cause wear. The movement wears the base sheet. The surface of the material must be able to withstand movement without being worn. In the current solution, gel-coat protects the sur-

face. In next section the significance of vaporizer in wear behavior and its structure are explained. (19)

The maximum length of vaporizer is 3.5 meters when the freezer is 3.75 meters long. Other lengths for the freezer are 2.5 and 1.88 meters. In freezers lamella division is 7-12 mm which is sparser than in fridges. Division is sparser because it prevents the decrease of cold power that can occur because of accumulated frost on the vaporizer. Vaporizers are usually melted by air melting and fans are kept on to decrease the melting time. When in freezers the melting has to be quick it is done by electricity or hot gas melting. Electrical resistors help the melt water to stay in liquid form and drain to sewer in electricity melting whereas the hot gas of compressor heats the vaporizer section and defrost water pool in hot gas melting. In neither of the melting methods vaporizer fans are not on. Electrical resistors are placed under the base. (20)

Described functions of vaporizer set certain demands to the base material. Base material has to sustain installation and maintenance that might cause wear. When the surface is exposed to load, the wear type can be determined. In **Figure 9** are introduced the types of loadings; mechanical, thermal and chemical. There are also categorized long and short term effect loadings and the types of wear causes. The **Figure 9** also shows the causes of wear, which are abrasion, adhesion, fracture, chipping, crack formation, diffusion and oxidation. Wear resistance is not tested, because there are a lot of different wear mechanisms and facilities are not enough for that. (21)

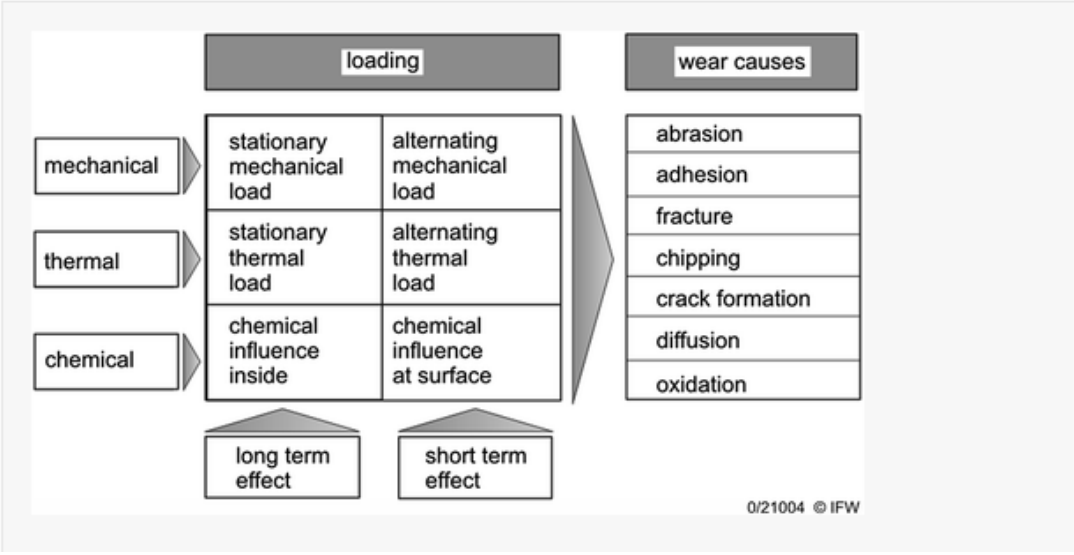

Figure 9. *Loading and wear mechanisms (21).*

4.6 Thermal conductivity

Thermal conductivity is a quantity that measures material's ability to conduct heat (22). Thermal conductivity of the base material is not significant factor as thermal insulator because the insulation of heat is executed by polyurethane layer. Even though GFRP composite has also great heat insulation properties it has not significance impact and new material option does not have to have similar thermal insulation properties. Thus material can be thermal conductor, like most of the metals are.

If there were a material which has very good heat storage capacity, for instance steel, it would cause problems with melting the freezer unless there would not be a heat source. During usage the material is in freezer temperature. Vaporizer is warmed up in melting process, but the base material remains cold. Melted water drops to the bottom and if it is cold it will solidify which is not desired. The base material has to be heat conductive enough in order that heat from heat source under the bottom warms it up and ensures that water can flow freely to sewer. In the worst case the way to the sewer is long and there must be several heaters. For example the longest type of remote freezer tank is 3.75 meter and the sewer is long distance from vaporizer. Heaters are usually thermal wires and generally used in all remote freezers. Metals are a good option when heaters are in use because they have good thermal conductivity and heat can spread to the bottom over a wide area, preventing ice from forming. With materials with low thermal conductivity, the heaters heat only locally, allowing ice to form in other areas. This phenomenon is especially pronounced when the thickness of the material with low thermal conductivity is large.

4.7 Formability

Formability describes how easy it is to shape a material to desired form. In metals, formability is affected by lattice structure and limited by fracture. Formability enhance in higher temperatures because the movement of dislocations is faster. Polymers can be divided in thermosets and thermoplastics which defines their formability. The shape of the product set the formability requirements for the base material. Formability method depends on material, since the methods of forming metals, polymers and composites differ greatly. As mentioned, the forming method of the GFRP composite is a hand lay-up method, and the shape of the base is built by laminating the mold.

The requirement for formability is certain structural issues that are mandatory. The shape of the base should be such that the melt water is directed to a certain groove

and can drain into the drain. Thus, the material and the method of rendering must enable this. The current solution has a large number of connection surfaces because GFRP is connected to a hot dip galvanized sheet. A new material solution could reduce these joint surfaces, but requires re-design of the structure. Joint surfaces are to be avoided to minimize the potential for urethane to leak out of the structure during casting. Formability is not elaborated in this thesis, because the possible re-design may be done with new material. For future research, there are a table of shaping, joining and finishing different material groups in the APPENDIX B.

5. SELECTED TEST MATERIALS

This chapter introduces the materials chosen for to the tests according to chapter 3 and analyzes their features listed in chapter 4. First various polymeric materials are introduced, including common plastics and engineering plastics. After that, the metals and their alloys will be discussed, and finally the solutions provided by various coating options and surface treatments. Materials, which prices are approximately the same or cheaper than the current solution, have been under investigation, for example, carbon fibre reinforced composite is rejected due to their high cost.

5.1 Polymers

Generally polymers have worse dimensional stability than metals in unstable temperatures therefore the variation in dimensions has to be taken into account to prevent cracks and fractures. Even though GFRP has epoxy matrix, in pure polymers without reinforcement the percentage of polymer is higher than in GFRP, which probably increases changes in dimensions. Therefore, polymer as the replacer sets demands for designing.

Corrosion resistance is one of the main reasons why GFRP has been selected as a base material. Generally polymers have good corrosion and chemical resistance and they are thermal insulators. If the polymer is rigid by its nature the thickness can be thinner and then the material consumption is reduced. On the other hand, if the polymer is more flexible the thickness has to be thicker and consumption increases. If the material is too thick the heat from the thermal wires is not conducted and the melting water will freeze to the base. The balance has to be found to make the most optimal decision. As discussed in chapter 4.4, glass transition temperature has effect on polymers mechanical behavior. **Table 1** shows the glass transition temperature for the test polymers, including GFRP.

Table 1. *Glass transition temperatures of test polymers (40).*

Material	Glass transition temperature [°C]
GFRP	~60-170
PE 300	-95
PE 1000	80
ABS	105
POM C	-60

Engineering plastics are usually harder and denser than common plastics. From test materials engineering plastic is polyoxymethylene (POM) and common plastics are polyethylene 300 and 1000 and acrylonitrile-butadiene-styrene (ABS).

5.1.1 Acrylonitrile-butadiene-styrene (ABS)

Acrylonitrile butadiene styrene (ABS) is a common plastic and it is amorphous from its structure. ABS consists of three monomers (terpolymer): acrylonitrile, butadiene and styrene. Acrylonitrile provides chemical resistance and heat stability whereas butadiene toughness and impact strength. Rigidity and process ability of ABS is provided by styrene. Polar solvents can harm its structure. (23)(24)

ABS has a lots of advantages, for instance it is 100% recyclable, non-toxic, harmless and low cost. Acrylonitrile itself is almost as toxic as cyanide, but polymerization with butadiene makes it harmless. ABS has a lower thermal expansion than other polymers and its impact resistance is highest of all polymers. Forming of ABS is easy and its tensile strength is high. (7)(24)

It is possible to make ABS resistant to UV-radiation with stabilizers. ABS is hygroscopic in nature, so before starting the thermoforming process, moisture must be removed by oven drying. (7)(23)(25)

5.1.2 Polyethylene (PE)

Polyethylene (PE) materials are thermoplastic, semi-crystalline and usually soft but strength can be increased by increasing the molecular weight of the polymer or by adding additives/fillers. They can be divided in low density (LDPE) and high density polyethylene (HDPE). In this thesis the high density polyethylene is examined because of its strength is four times higher compared to low density polyethylene. (26)

High-Density Polyethylene (HDPE) is polyethylene with high molecular weight. PE 300 and 1000 are selected as test materials and numbers 300 and 1000 refer to molecular weight. In fact, PE 1000 is Ultra-High-Molecular-Weight (UHMW). The higher the molecular weight is the better are the mechanical properties of polyethylene. HDPE has higher hardness and rigidity than lower density materials. The limit of molecular weight for low density materials is 300,000 g/mol. The compressive strength is also high. HDPE is a food grade with FDA requirements. HDPE has a low coefficient of friction and, when combined with high molecular weight, provides very good wear resistance of the material. (27)

HDPE has particularly good impact strength, because according to standard DIN EN ISO 179-1eU it does not break. It is easy to machine and has inherently good self-lubricating properties. HDPE could also be a good base material because it has good stress cracking resistance and ability to resist corrosive environments. It does not withstand strong oxidizing acids, which fortunately does not pose a risk for the particular application. Brine that may leak from damaged packages will not cause any change in the material. HDPE has a wide range of possible processing methods; hot gas welding, fusion and butt welding, ultrasonically sealing die cutting, machining with wood- or metalworking tools, vacuum forming and thermoforming. (27)

HDPE has low moisture absorption which is important for the base material not to be water permeable or to change its dimensions due to swelling. In general, HDPE is stronger than low-density polyethylene (LDPE), but at low temperatures, LDPE has higher impact strength. There is also a risk of distortions due to the high degree of crystallinity. The high degree of crystallinity also increases the sensitivity to different cooling rates, especially across the walls of rotomoulded products. The shrinkage is also greater for HDPE than for LDPE. The disadvantages of HDPE are its susceptibility to stress cracking and its stiffness poorer than other common plastics. In addition, it has a high mould shrinkage and low UV resistance. The exposure to UV light is not high in this application so it does not have high impact. (27)

5.1.3 Polyoxymethylene (POM)

Polyoxymethylene (POM), also known as acetal, is an engineering plastic with precise dimensional stability at various temperatures. The POM-molecule consists of a repeating $(CH_2O)_n$-molecule, which makes the structure highly crystalline. High degree of crystallinity allows good formability. (7)

POM has high stiffness, fatigue resistance and water repellency compared to common plastics but its impact and wear resistance are better poorer. POM would be good for this application due to its formability, fatigue resistance and stiffness. It can be molded by injection molding and sheet molding. For example, bearings and gears are often made from POM, and making a larger profile is more atypical. Due to its hygroscopic nature in the manufacturing process, drying in the oven is recommended. POM requires co-polymerization or addition of blocking groups to prevent its degradation. (7)

5.2 Aluminum alloys

Aluminum is the world's second most important metal in the economy after steel because it is lightweight and has high strength. It is relatively inexpensive but still twice as expensive as regular carbon steel. Aluminum has excellent thermal conductivity and formability. It is versatile due to its numerous alloys. Aluminum weighs only one third of the weight of steel. Alloys can be obtained with much different strength. The low density and relatively high strength offers aluminum strength-to-weight ratio benefit. Digging and refining aluminum into pure metal is energy consuming, but it is easy to recycle at low cost. (7)(8)(28)

Due to the reactivity of aluminum, it forms an oxide layer on its surface which protects it from corrosion in water and under acidic conditions. If the oxide layer is destroyed for any reason, aluminum is more susceptible to corrosion. The acid resistance is good, but some alkaline environments can damage aluminum. Freezer conditions can be compared to marine conditions, which are alkaline. In addition, detergents include alkali. Therefore, aluminum should be tested when pH is above 7. Inhibitors help aluminum to withstand mild alkaline conditions. In **Figure 10** are presented corrosion resistance of aluminum at different pH in different chemicals. With long-duration tests mass losses could be verified. (7)(28)

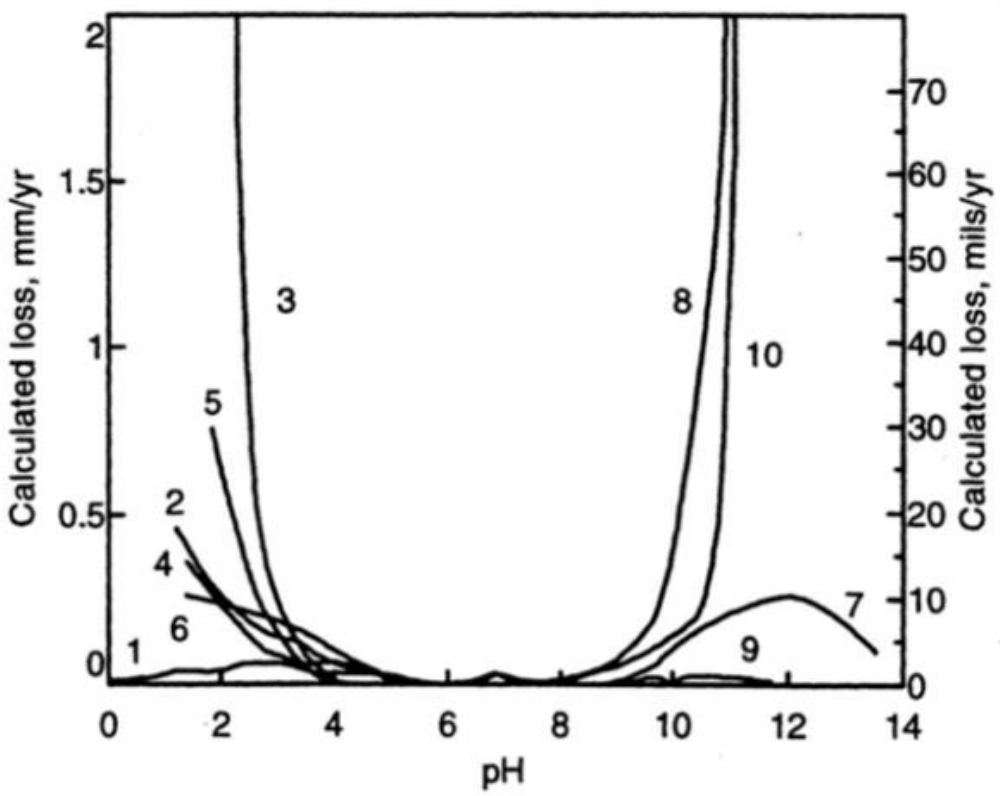

Figure 10. *Corrosion resistance of aluminum. Different chemicals: 1) acetic acid; 2) hydrochloric acid; 3) hydrofluoric acid; 4) nitric acid; 5) phosphoric acid; 6) sulphuric acid; 7) ammonium hydroxide; 8) sodium carbonate; 9) sodium disilicate; 10) sodium hydroxide. (8)*

Aluminum has a good, reflective surface which makes it an effective barrier against thermal radiation. In general, aluminum does not need a protective coating. For applications where the natural surface quality of aluminum is not sufficient, many different coatings can be used, such as chemical, electrochemical and paint finishes. (28)

The machinability of aluminum is really easy, and it is more advantageous than cheaper materials in terms of workability. Thin sheet thickness adjustment is really easy and can be made even thinner than paper. Formability is one of the main advantages of aluminum for this application. Aluminum can be machined at the speed and ways that machine tools give. There are also many methods of joining; riveting, welding, brazing and soldering. (28)

Aluminum alloys can be divided in two groups: wrought and cast alloys. Wrought alloys are selected for test materials, because cast alloys might be recycled or new material when the history is unknown and therefore their performance is also. They are also hard to anodize. A common rule is that the more pure the aluminum is, the more corro-

sion resistant it is. Copper is the most harmful alloying element for corrosion resistance and magnesium the least. Therefore, 2000 series is poor option for the application because its main alloying element is copper whereas 5000 series is excellent due to magnesium. 3000 series has manganese as the main constituent and corrosion resistance is good. 6000 series has good corrosion resistance but not as good as 5000 series has. It might be still enough for the application. 6000 series has moderate strength and heat treatability. (29)

The color of anodized 3000 series alloys is not stable, it might vary from light grey to brown and therefore 3000 series alloy was ordered without anodizing as was 6000 series. In 6000 series, T6 treatment enhances machinability but it is not so suitable for anodizing. 6000 series is usually used to produce profiles by extruding. (29)

Some original selections were replaced by supplier's suggestions due to availability. Also two aluminum alloys, Coating 4 and 5, were selected because they are supplier's suggestions. The tests are intended to compare potential 3-; 5- and 6-series aluminum alloys as they are corrosion resistant grades and 5-series alloys are best anodized if their intrinsic performance is not sufficient.

The main alloying element in 3-series alloys is manganese, 5-series magnesium and 6-series magnesium and silicon. The temper designation system tells about the cold and hot working history of wrought and cast alloys. Labeling is required as it has a significant effect on the properties of the alloys. Abbreviations means: F= manufactured; O= annealed; H= strain-hardened (for wrought alloys only); W= solution heat treated and T= heat treated to obtain stable tempers. Precise explanations of test materials' abbreviations are explained in **Table 2**.

Table 2. *Heat treatment temper designations.*

Heat treatment temper designations	
T6	Solution heat treated then artificially aged
H111	Applies to products which are strain-hardened less than the amount required for a controlled H11 temper
H22	Strain hardened and partially annealed, quarter hard
H14	Strain hardened only, half hard
H44	Strain hardened and lacquered or painted, half hard
H16	Strain hardened only, three-quarters hard

The best corrosion resistance is in pure aluminum, but its strength would be too poor. With manganese alloy 3-series provide moderate strength without compromising corrosion resistance. Magnesium provides the 5-series alloys with moderate strength and corrosion resistance. The corrosion resistance is equally good as pure aluminum in al-

loys where magnesium remains in the solid solution certain amounts or precipitates into Al_8Mg_5 particles uniformly around the matrix. Corrosion resistance is even better than pure aluminum in salt water and alkaline conditions. In 6-series aluminum alloys, magnesium silicide may be formed with suitable proportions of magnesium and silicon. The precipitate causes hardening, which results in moderate strength and excellent corrosion resistance. They are heat-treatable and have good formability. (8)

5.2.1 Aluminum sandwich structure

Aluminum can be also used in various sandwich structures that combine aluminum with, for example, polyethylene. The laminate combines strength with a lightweight structure where the outer casings are generally metal and centermost polymer material, as presented in **Figure 11**. The commercial composite in question is a suggestion from a supplier of polymers to be included in the comparison. Alucobond ® is semi-finished product which is anodized by at least 20 µm thick layer, according to DIN 17611 (*information from supplier*). The used aluminum is 5005 alloy. (8)

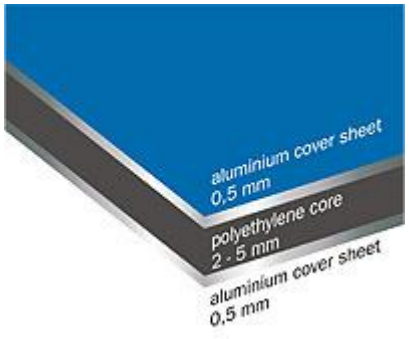

Figure 11. *Structure of Alucobond (31).*

5.3 Coatings and surface modifications

Coatings and surface modifications are one way to increase desired properties. Coatings are mainly used to protect the substrate material from corrosion, but they can also provide an improved appearance. Anti-corrosion coatings can be divided into organic and inorganic coatings. However, the interface is inaccurate, as inorganic coatings often contain organic ingredients and vice versa. Organic coatings include varnishes, lacquers and paints. (8)

Varnishes can be spirit varnishes containing synthetic or natural resins in solution or semi-solid oleoresinous varnishes in which the resin is combined with a solution and a

drying oil mixture. The pigment in the varnish is called enamel. Lacquer, in turn, is a cellulose ester solution and the pigment in the lacquer is lacquer enamel. The vehicle consists of resin, solution and drying oil, and the paint consists of them, additives and pigment. The paint pigment may be an inorganic pigment or metal powder, and additives include a drier, an extender and a plasticizer. (8)

The coating's defense mechanism is based on providing a barrier to reagents and a place for corrosion inhibitors, which helps the exposed surface. Paint protection allows diffusion of water, water vapor and atmospheric oxygen through the paint surface. This can be prevented by increasing the thickness of the paint surface and adding pigment and fillers to the paint formulation. (8)

5.3.1 Anodizing

Anodizing bases on electrochemistry and in the process aluminum is converted into aluminum oxide (Al_2O_3). Also titanium and magnesium can be anodized. Anodizing protects the aluminum surface while making the surface aesthetically pleasing. Most of anodizations are weldable. (28)(32)

The aluminum surface must be thoroughly cleaned before being immersed in the sulfur solution. The electric current passes through the aluminum sheet and causes aluminum surface to form an alumina layer. Current strength, temperature of sulfur solution, and absorption time determine the thickness and hardness of the anodization. Hardcoat anodized coatings are relatively thicker than most anodic coatings: even 50 µm compared to normal 5-18 µm. In this work, test samples are anodized with normal thickness. (28)(32)

Anodizing is a relatively environmentally friendly coating method compared to other metal plating processes. The finished anodized surface is non-toxic and the solutions used for anodizing can be recycled and reused. (28)(32)

5.3.2 Galfan

Galfan-coating is an alloy of zinc and aluminum with excellent corrosion protection and formability compared to, for example, zinc coating. Coating includes 95% of zinc and 5% of aluminum. Due to the composition, the microstructure of the coating is lamellar and the adhesion of the coating is good due to the aluminum/zinc alloy ratio. The coating guarantees a longer service life and has good weldability and formability. It has a

cellular pattern on its surface (**Figure 12**). Due to the flexibility of the coating, it is well suited for deep drawing. Galfan-coating is suitable for steels. (33)(34)

The coating is applied to both sides of the metal sheet by hot dip galvanizing. The coating protects the cutting edges, damaged areas and areas that are constantly exposed to corrosion. The coating is very tightly attached and does not crack easily. The lamellar microstructure enables roll forming, deep drawing, profiling and bending. The coating remains intact during molding. (33)

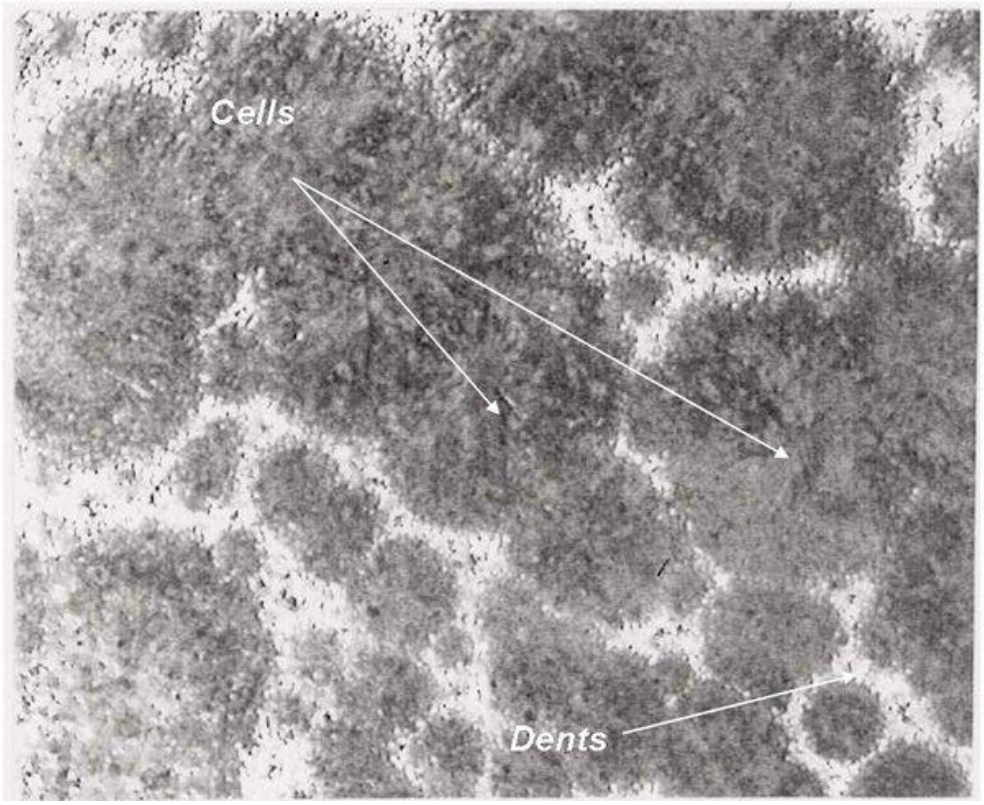

Figure 12. *Cellular pattern on galfan-coating (34).*

5.3.3 Powder coating

Powder coatings are durable and protect the base material from corrosion. Successful powder coating requires a clean and well-prepared substrate. Before applying the powder coating, dirt and oxides must be removed to ensure the good quality of coating. Alkaline cleaners can remove dirt, but if tenacious metal oxides are present on the surface they must be removed mechanically. Mechanical cleaning is performed before using an alkaline cleaner. (35)

Once the surface is clean and rinsed, the chemical conversion process is used to improve the adhesion between the coating and the metal. Ferrous substrates are pre-

treated using the iron phosphate or zinc phosphate process. The latter provides better interface between coating and metal. In phosphate-based processes, rinsing is performed twice and chemical binder is used to provide the best corrosion protection. (35)

Epoxy-based powder coatings offer the best chemistry to prevent corrosion and tests are performed by fine-grained epoxy powder paint. Availability is from the company's own paint shop. At elevated temperatures (melting point of the powder is 100 °C), the powder melts and cures to form the final paint film. The film is chemically and mechanically resistant and retains its gloss even under outdoor conditions. The thickness of the film varies in range 80-480 µm. According to directions for use, powder coating sustains well 10% sodium hydroxide and 10% sodium chloride solutions. (35)

The highest corrosion protection is achieved with a 2-layer system. The system has a primer, which is typically epoxy-based and has a top coat. The coating may be polyester, polyurethane, acrylic or fluoropolymer, depending on the conditions. Their UV duration varies from 10 to 20 years, but under freezer conditions UV radiation is not a major threat. A single-layer powder coating is believed to be sufficient for these conditions, but in a possible further study this could also be tested if a single coat is not sufficient. (35)

6. EXPERIMENTAL PROCEDURE

The performed tests were selected to measure the required properties in chapter 3. Hot dip galvanized steel specimens were powder coated for testing and 5000 series aluminum specimens were coated by a subcontractor. The supplier's specially coated aluminum came pre-cut and coated.

The samples were prepared as required for the test before starting. First, all samples were mechanically labeled to separate the different materials. For the corrosion and the alkaline environment test, all specimens were marked with a hole and a scratch to track where the impacts of solutions would have been preferably begun. The test plan is presented in **Figure 13**.

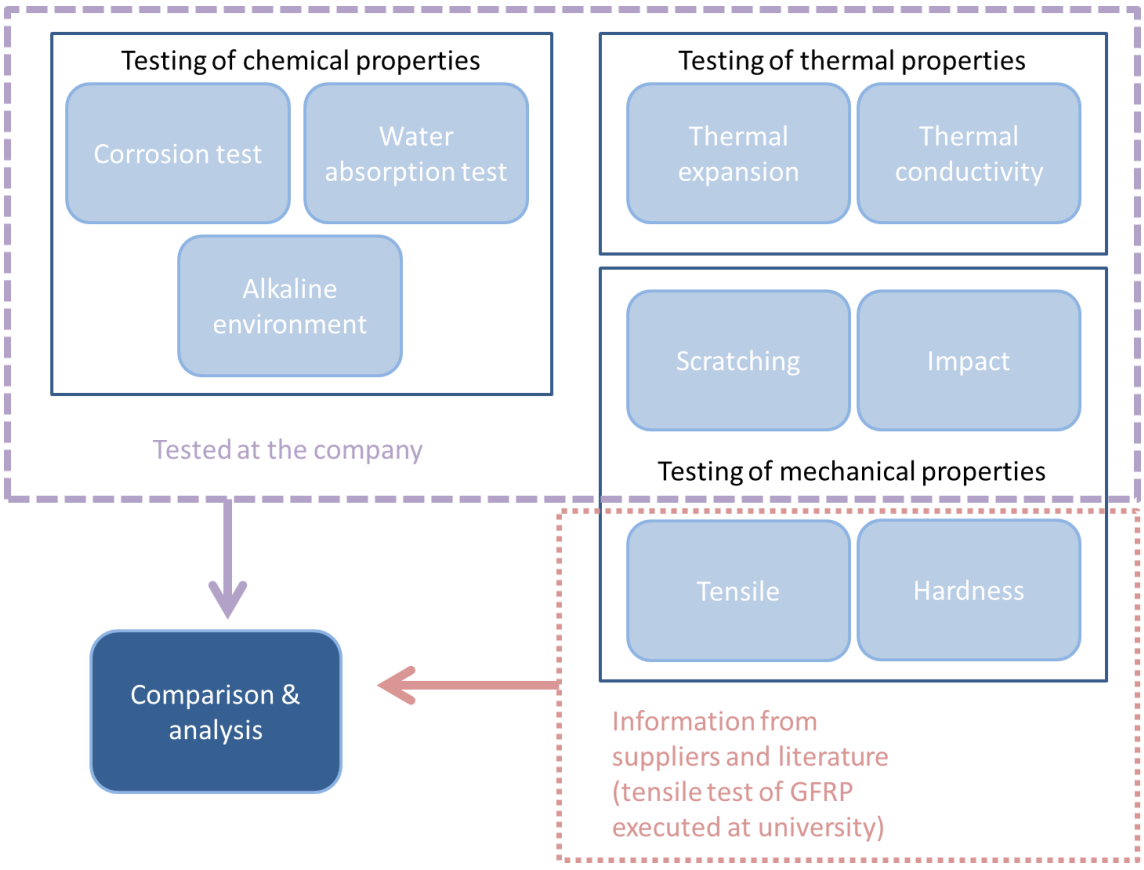

Figure 13. *Categorized test plan.*

6.1 Materials

Table 3 shows which tests were performed for each material. The corrosion test was carried out on metal materials because as generalized, polymers are free of corrosion. The water absorption test was performed on plastics and was not performed on metals as they do not tend to absorb moisture. Coatings are not supposed to absorb moisture either. The alkaline environment test was performed on all samples and especially the aluminum properties tend to weaken under alkaline conditions. The heat conduction test was performed on all materials in order to obtain comparable data from all options. The thermal expansion test was only performed for GFRP because it does not have a known thermal expansion coefficient to calculate the amount of expansion. The scratching test was performed on each material to ensure surface quality, as was an impact test. The impact test also measures toughness of the materials. The tensile test was performed only on GFRP at university and other results were obtained from literature. Coatings are not expected to significantly affect the properties achieved from tensile test.

Table 3. *Distribution of materials for different tests.*

		Test						
Material	**Thickness**	*Corrosion*	*Water absorption*	*Alkaline environment*	*Thermal conductivity*	*Thermal expansion*	*Scratching*	*Impact*
Sample size	[mm]	*50 *50*	*50 *50*	*50 *50*	*200 *500*	*200 *500*	*200 *500*	*200 *500*
GFRP	~3		X	X	X	X	X	X
PE 300	3		X	X	X		X	X
PE 1000	3		X	X	X		X	X
ABS	3		X	X	X		X	X
POM	3		X	X	X		X	X
Alucobond	3	X		X	X		X	X
Aluminum 1	1	X		X	X		X	X
Aluminum 2	1	X		X	X		X	X
Aluminum 3	1	X		X	X		X	X
Aluminum 4	1.5	X		X	X		X	X
Aluminum 5	1	X		X	X		X	X
Coated								
Coating 1	1	X		X	X		X	X
Coating 2	1	X		X	X		X	X
Coating 3	1	X		X	X		X	X
Coating 4	1	X		X	X		X	X
Coating 5	1	X		X	X		X	X
Powder coating	1	X		X	X		X	X
Galfan	1-1.5	X		X	X		X	X

6.2 Test method arrangements

This section describes the test setup and how to evaluate the test results. The tests were run in the company testing laboratory and the equipment required by the standards was not available. Due to that, the results are qualitative rather than quantitative, since the purpose of the test was to arrange the materials on the basis of their success.

6.2.1 Corrosion test

Corrosion test measures corrosion and chemical resistance. Durability of corrosion is often measured by mass loss as a function of time. However, mass losses occur slowly, speaking of months, and therefore corrosion events were mainly evaluated visually in this thesis. The specimens were placed in the sodium chloride (NaCl) -solution thereby that half of the sample was in solution and half was above solution to observe the behavior of the material in solution, interface and air, as presented in **Figure 14**. The hole was not required to be half submerged, as the space was closed and there was 100% relative humidity, whereby the effect of air humidity may have also caused corrosion into hole. The corrosion rate was controlled by the concentration of the solution and temperature. The test was started at 35 °C in a 5% solution, since the conditions for a standard salt spray test were similar. **Figure 15** shows the actual test arrangements. The duration of the test depended on how long it took to get differences in corrosion behavior between materials.

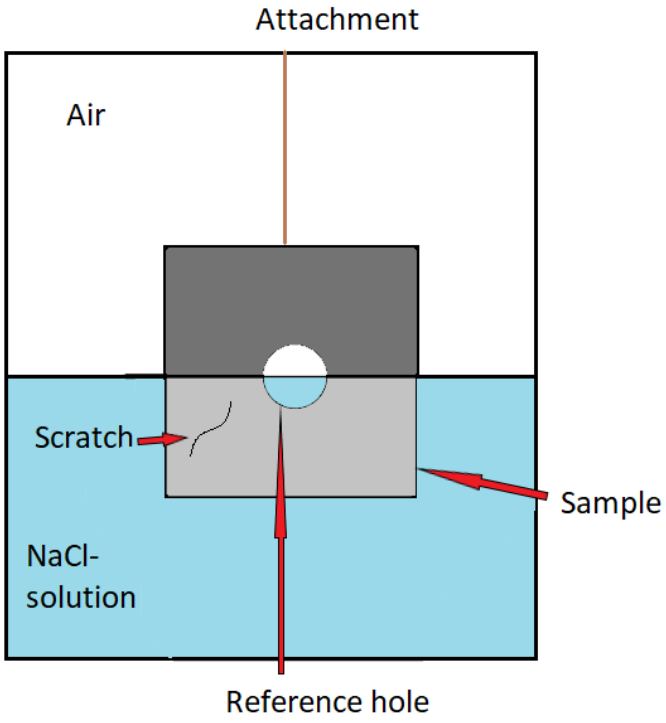

Figure 14. *Corrosion test arrangement.*

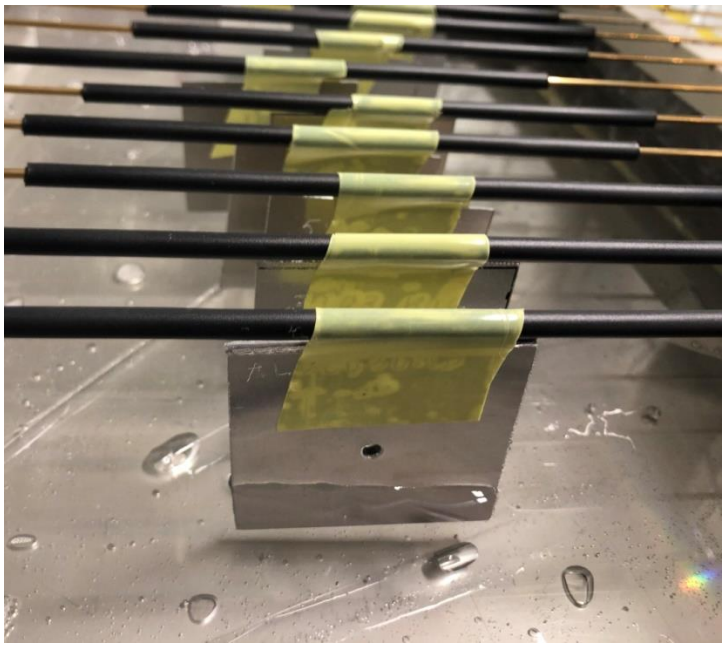

Figure 15. *Test pieces in 5% sodium chloride (NaCl) solution at 35 °C.*

6.2.2 Alkaline environment test

Alkaline environment test measures chemical resistance. The alkaline environment test was performed in the same way as the corrosion test, but the solution was alkaline by sodium hydroxide (NaOH), see **Figure 16**. The solution had a pH of 8-9 which was verified with pH paper. The test temperature was approximately 20 °C. The test duration depended on how long it took to get differences between durability of materials in alkali.

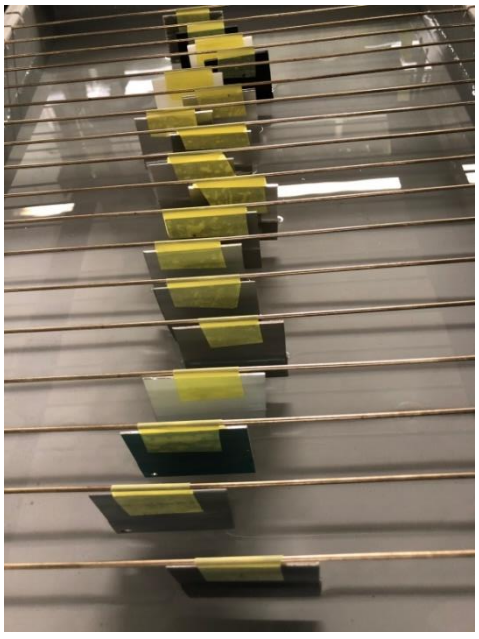

Figure 16. *Samples in alkaline solution.*

6.2.3 Water absorption test

Water absorption test is part of testing dimensional stability. The water absorption test was carried out by weighing the polymer samples before the test and then completely immersing them in distilled water (**Figure 17**). The samples were weighed after 24 and 48 hours immersion at 23 °C. To ensure equal starting point in moisture, the samples were baked in the oven at 80 °C for two hours. Test arrangements were based on standard ASTM D570.

The drying temperature was selected based on the fact that no melting point of any material is close to it or degree of crystallinity would have changed significantly. A few of the test polymers are semi-crystalline: PE 300, PE 1000 and POM C. When surrounding temperature is between melting and glass transition temperature, the mechanical properties depends on crystallinity. Degree of crystallinity might change in that temperature range, which might affect to the water absorption properties. (36)

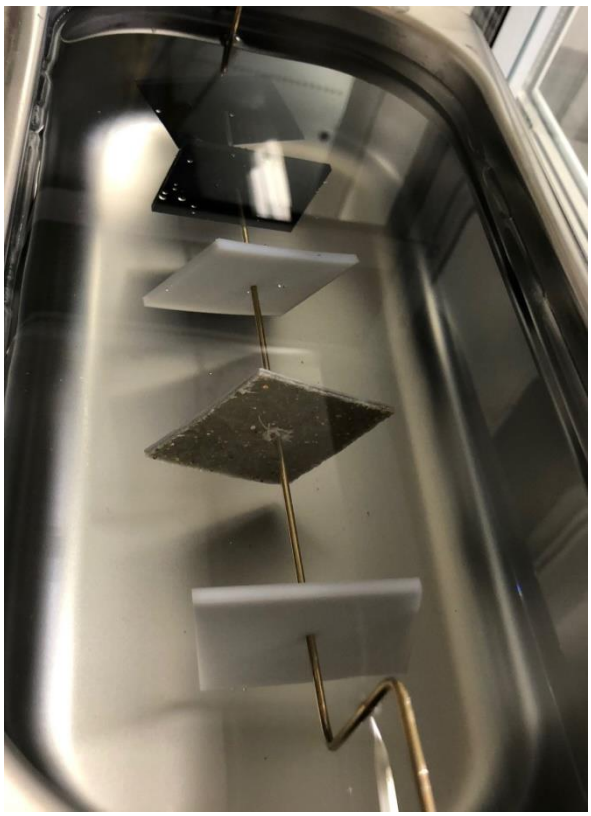

Figure 17. *Water absorption samples in distilled water.*

6.2.4 Thermal expansion test

Thermal expansion test is part of testing dimensional stability and helps to design the structure. Amount of thermal expansion of a base material was evaluated by thermal

expansion coefficients. Thermal expansion coefficient of GFRP was not known exactly and therefore the changes of dimensions were measured in temperature range 40 °C for GFRP. Anodization or coatings are not expected to affect thermal expansion. The thermal expansion of galfan-coated and powder-coated steel was calculated using the coefficient of thermal expansion of ordinary carbon steel. Thermal expansion coefficients are presented in **Table 4**.

Table 4. *Thermal expansion coefficients of test materials (30).*

Material	Thermal expansion coefficient [1/K]
GFRP	?
PE 300	$18*10^{-5}$
PE 1000	$20*10^{-5}$
ABS	$6.5*10^{-5}$
POM C	$13*10^{-5}$
Aluminum 1	$2.31*10^{-5}$
Aluminum 2	$2.37*10^{-5}$
Aluminum 3	$2.37*10^{-5}$
Aluminum 4	$2.38*10^{-5}$
Aluminum 5	$2.31*10^{-5}$
Coating 5	$2.39*10^{-5}$
Coating 4	$2.01*10^{-5}$
Alucobond	$2.4*10^{-5}$
Steel	$1.2*10^{-6}$

6.2.5 Thermal conductivity test

Thermal conductivity test measures thermal conductivity and gives information about the needed amount of thermal wires. The thermal conduction test aimed to simulate how well the heat was dissipated by thermal wires. Thicknesses varied between materials due to availability, so results are approximate. The temperature on the surface of the material was measured by thermocouple sensors. Three sensors were mounted on each sample of material as follows: one for the thermal wire, the second 2.5 cm and the third 5.0 cm from the thermal wire. The locations of the sensors are shown in **Figures 18**: A-sensor was on the thermal wire. The measurement was at room temperature and the power of the heating wire was 60 watts. The material was in the air at the

measuring point so that the surrounding materials did not affect the results. Arrangements are presented in **Figure 19**.

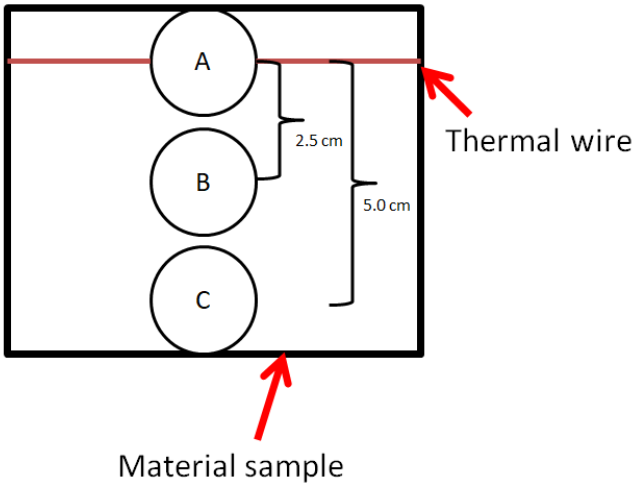

Figure 18. *Locations of sensors on the sample.*

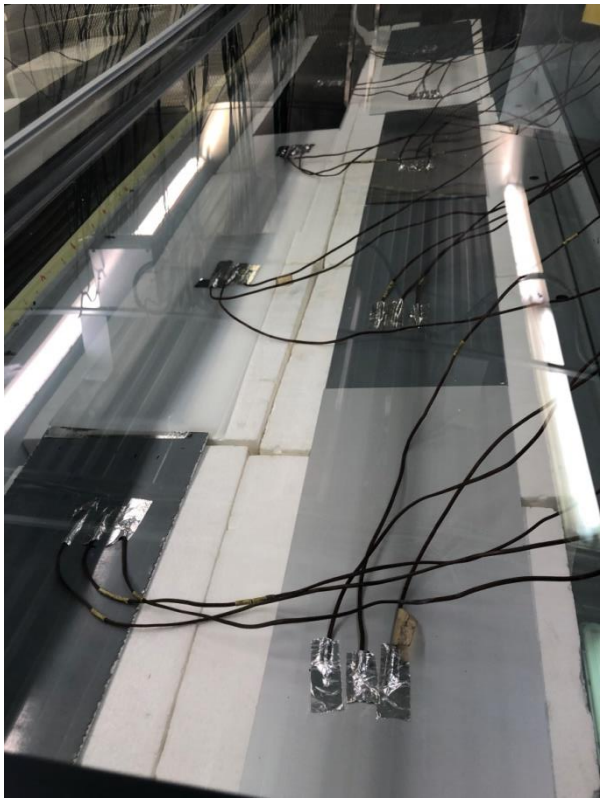

Figure 19. *Thermal conductivity test arrangements.*

6.2.6 Scratch test

Scratch test measures surface quality, hardness and in a way short-term wear resistance. The scratch test was carried out with rotating motor around which the material samples were overlapped (**Figure 20**). The engine rotated a shaft with scratching glass component weighing 650 g at one end. The rotation speed was 20 cm per second, and the scratch test took approximately 35 minutes, resulting in 500 rounds. The rotation speed, the mass of the scratching component, and the duration of the test were determined experimentally. The samples were screwed in the platform to prevent motion.

Figure 20. *Scratch test arrangements.*

6.2.7 Impact test

Impact test measures mechanical shock resistance and the influence of temperature in mechanical behavior. The impact test was carried out with a hammer of 1000 g, which was dropped at an angle of 110 degrees to the sample. The length of the hammer shaft was 22 cm. The specimen was placed into a vice at angle of 90 degrees from horizontal axel. The exposed part of sample was 4 cm above the vise. The space between the hammer and the vise was 1.5 cm. Impact testing of each sample was videotaped with a camera to estimate the deflection of the sample due to impact. The video made possible to estimate the proportions of elastic and plastic deformation. Test arrangements

are in **Figure 21**. The same test arrangements were performed for samples at room temperature and -20 °C.

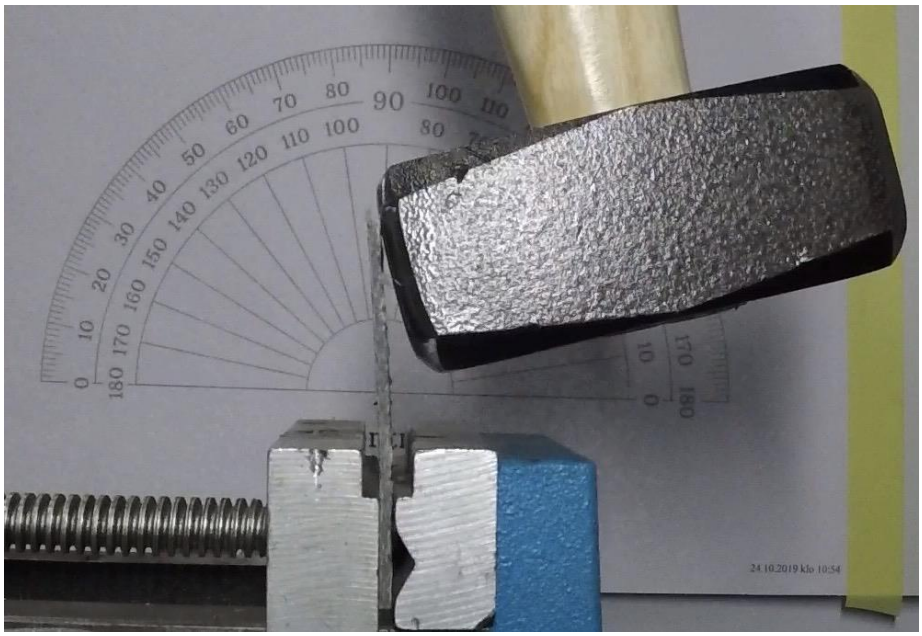

Figure 21. *Impact test arrangements.*

6.3 Theoretical tests

Tensile test results and hardness values were from literature and suppliers, but there are explained the theoretical background of these two tests. Only GFRP was tensile tested at Tampere University.

6.3.1 Tensile test

Tensile testing is common way to ensure mechanical properties of materials in material selection process. In chapter 4.4 is described that toughness and rigidity are desirable properties and by tensile test they can be measured. (37)

There exists a standard for tensile testing of reinforced thermosetting plastics, ASTM D5083. According to the standard, width of test specimen is 25 mm and length 250 mm but at university the length was 240 mm. Thickness of the specimen can be at range 2-14 mm and in this case it was approximately 3 mm. The ends of samples were strengthened in order that they sustain better. (38)

The aim was to measure force which was demanded to break a sample and measure how much was the elongation of the sample before breaking point. Tensile test produces stress-strain-curve, from where Young's modulus can be determined. Physical

properties depend on temperature of the circumstances, but in this thesis the temperature of tensile test conditions was room temperature because most of them were from literature or supplier. Specimens are placed between grips of the test machine and they are pulled until failure. Test rate is determined according to material specification but default test rate is 5 mm/min. At the university it was 1 mm/min. Although modulus determinations are done by test rate 2 mm/min. Extensometer or strain gauge are used to determine elongation and Young's modulus. A lot of information has been obtained on the tensile test: fracture toughness, yield strength, elongation at break, Young's modulus and tensile strength. (38)

According to tensile test data strain-stress –chart can be drawn. Engineering stress and strain as well as true stress and strain are calculated from tensile test data, but the difference between them is that engineering values do not take into account the decrease in cross-sectional area. Engineering strain is calculated as follows:

$$\varepsilon_E = \frac{\Delta L}{L}, \quad (3)$$

where ∆L is change in dimensions of extensometer and L original length between holders of extensometer. Engineering stress is calculated as follows:

$$\sigma_E = \frac{F}{sample\ thickness \cdot width\ of\ the\ sample}, \quad (4)$$

where F is load of the test. True strain is calculated:

$$\varepsilon_T = \ln(1 + \varepsilon_E)\ , \quad (5)$$

and true stress:

$$\sigma_T = \sigma_E \cdot (1 + \varepsilon_E). \quad (6)$$

(38)

6.3.2 Hardness test

Hardness test gives information about surface quality and scratching resistance. Brinell hardness test results from literature were utilized and they follow standard SFS-EN ISO 6506-1. It is the oldest hardness method and the standard 10 mm diameter tungsten carbide or steel spherical intender is used, when the weight of the load is 3000 kg. The time how long the load is applied is 30 seconds. The method to calculate Brinell hardness is presented in **Figure 22**. (15)

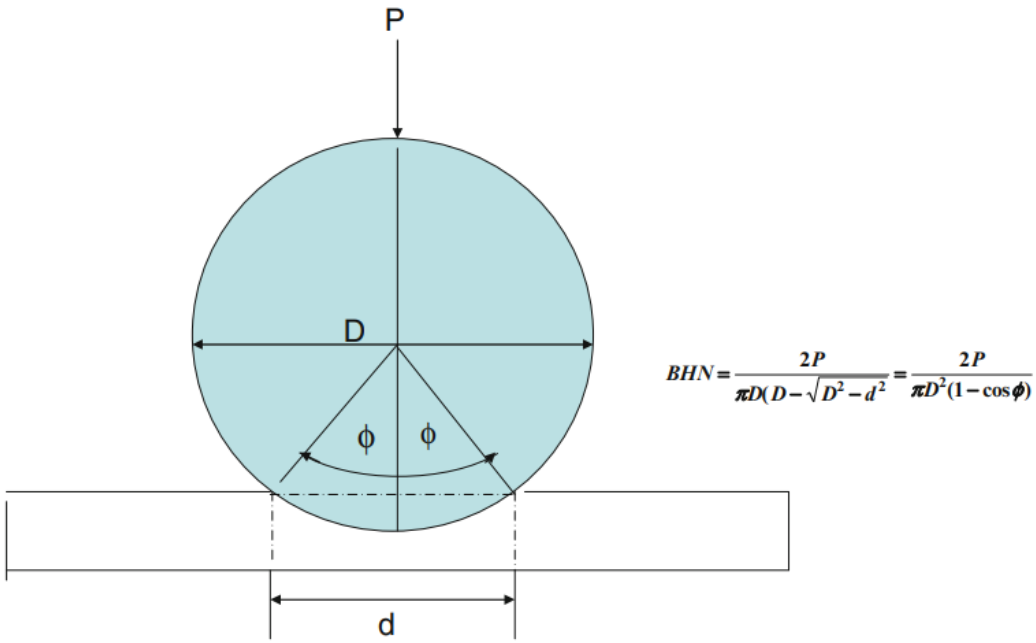

Figure 22. *Calculation of Brinell hardness (15).*

7. RESULTS AND DISCUSSION

In this chapter are introduced the results of performed tests that are described in chapter 6. The results are divided into three parts: chemical, thermal and mechanical properties.

7.1 Chemical properties

Chemical properties consider changes in materials due to corrosion, water absorption and alkaline environment tests. As mentioned in chapter 4, corrosion test measures corrosion resistance, surface quality and chemical resistance. Water absorption in turn is part of dimensional stability including thermal expansion and uniformity of manufacturing. Alkaline environmental test gives information about chemical resistance and surface quality.

7.1.1 Corrosion

Cleansing of samples was done by acetone and ultrasound. Microscope images provide more accurate information of plain aluminum alloys after corrosion test.

As mentioned, Table 3 shows the corrosion tested materials. Uncoated aluminum alloys seemed to suffer from the test the most, as expected. Typical corrosion types for aluminum are pitting corrosion, waterline corrosion, crevice corrosion and stress corrosion. Only pitting corrosion was detected in this research. Corrosion can be prevented by an appropriate alloy, heat treatments, appropriate design and protection. In aluminum alloys there appears also blackening, which is not an actual corrosion type. It is an aesthetical hindrance, which occurs in outermost oxide layer and has no impact in corrosion resistance of aluminum. It cannot be avoided but it can be removed in acidic environment so it is reversible phenomenon. Blackening is caused by the structure of outermost oxide layer and the presence of magnesium decreases it because aluminum is nobler than magnesium which makes it anodic. Cathodic elements and additives increase the blackening. It is not known an aluminum alloy which would not be prone to blackening. Solution has an effect on blackening: if it includes bicarbonates HCO_3^- and pH is in range 8-9 the blackening occurs. Blackening can be said to be adsorption of

bicarbonates into porous oxide layer. Blackening is milder with less electronegative substance, such as silver, stainless steel or copper. On the other hand, if aluminum is cathodically protected by sacrificed magnesium, the blackening is prevented. As mentioned, acidic environment can remove blackening. (39)

Pitting corrosion is easy to notice in aluminum, because pits are white due to alumina. Pits form when aluminum is placed in aqueous environment: water, seawater, rain water or humidity. Especially stagnant water expose to pitting, like in this test. Types of water, composition, temperature and flow of water have an impact on corrosion behavior. Types of water are fresh water, distilled water, brackish water, waste water and seawater. Test water corresponds to seawater. (39)

Pits occur in the first weeks of exposure, but it is very hard to predict what happens next – pits might remain unchanged the next 25 years. Presence of chloride causes pitting. Particularly local rupture of the passive film is favorable for pitting. Chlorides are small and mobile and they penetrate easily into the oxide layer. Also presence of copper causes pitting, because it oxidizes aluminum which leads to pitting:

$3Cu^{2+} + 6e^{-} \rightarrow 3Cu$

$2Al \rightarrow 2Al^{3+} + 6e^{-}$

$3Cu^{2+} + 2Al \rightarrow 2Al^{3+} + 3Cu$

On the other hand, if the amount of copper is slight, it can decrease pitting. Mercury and lead become reduced like copper, manganese or cobalt have not impact and iron, chromium and zinc form a layer on aluminum without attack. (39)

Usually, deepening of pits decreases as time passes in natural environments, which means a long lifetime for aluminum. Pitting corrosion can be evaluated on the basis of three criteria: density of pit occurrence, the rate how fast pits are deepening and chance of pitting. Deepening is the most important factor for evaluation. In this thesis occurrence of pitting is observed. (39)

Corrosion rate is affected by temperature, electrical conductivity and pH. The stability of natural oxide film determinates corrosion resistance of aluminum. The temperature range when aluminum is exposed to pitting is from room temperature up to 80 °C but it does not guarantee that pitting occurs. Temperature has effect on the external layer of natural oxide film. Up to 70 °C, reaction between water and oxide layer leads to formation of bayerite ($Al_2O_3 \cdot H_2O$). Bayerite increases the thickness of oxide layer and

corrosion rate is controlled by the layer because corrosion rate follows parabolic law. According to parabolic law, the layer formation rate decreases as time increases. Corrosion rate can be zero or low in aggressive aqueous environment when steady state is achieved and situation is in equilibrium. (39)

Figure 23 shows all the uncoated aluminum alloys and **Figure 24** galfan-coated steel and Coating 4 144 hours corrosion testing. Other coated material remained unchanged.

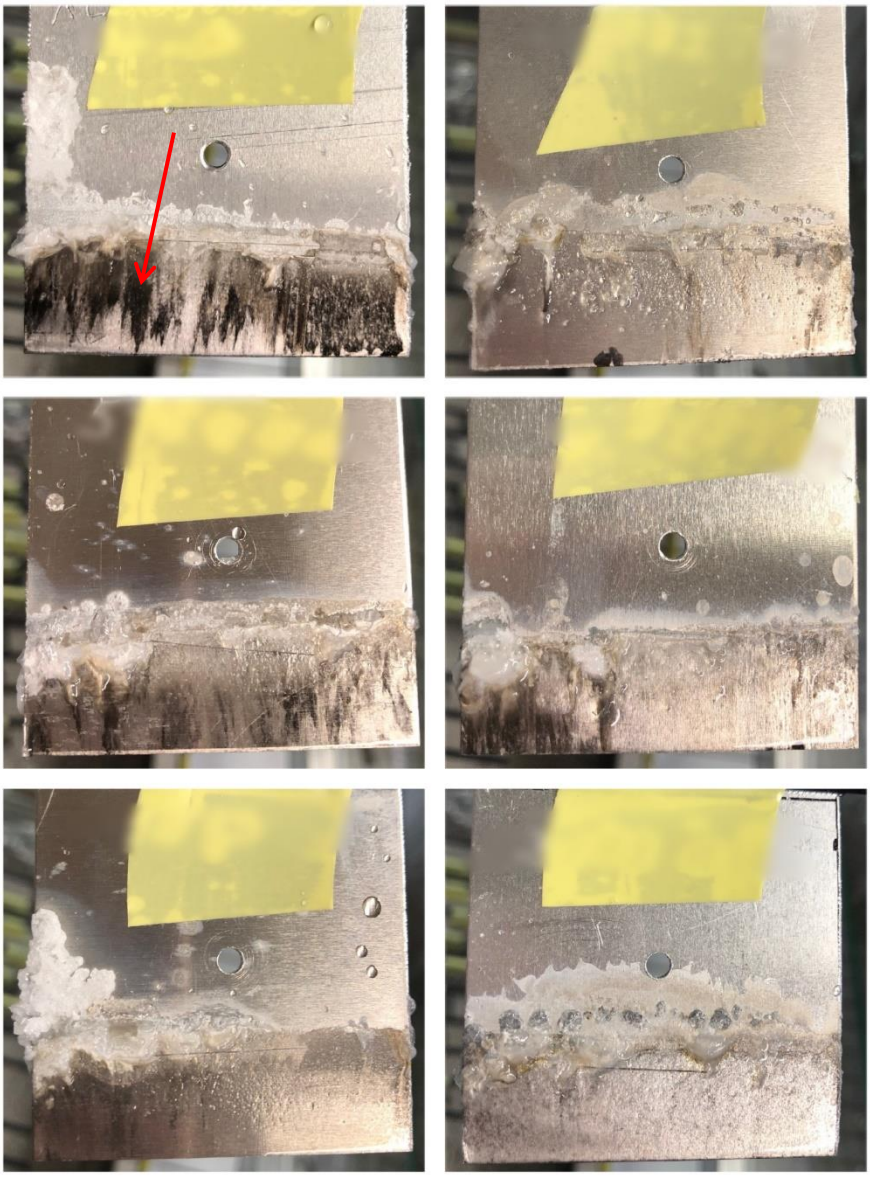

Figure 23. *Uncoated aluminum alloys after 144 hours of testing from left to the right from top to the bottom: Alucobond, Aluminum 5, Aluminum 2, Aluminum 3, Aluminum 4 and Aluminum 1. Blackening is the most clearly seen in Alucobond.*

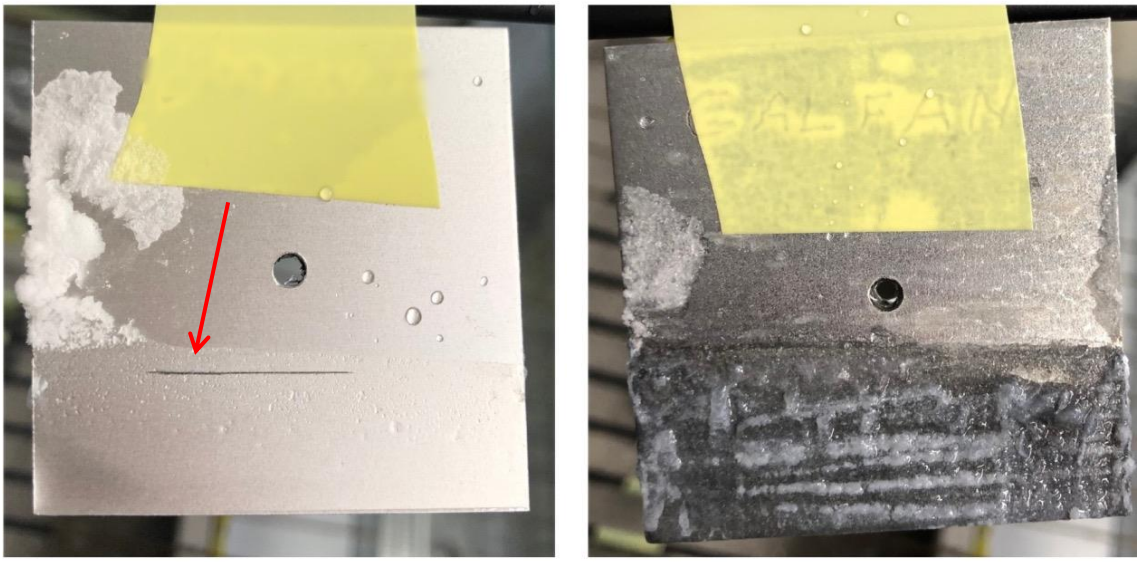

Figure 24. *Coating 4 and galfan-coated steel after 144h. Red arrow indicates the darkened scratch.*

The interface of Aluminum 1 showed the most changes with rust color and crystallized salt. Salt has no effect on corrosion behavior. Blackening was not observable. In 32X magnification of Aluminum 1 might have occurred slight and sparse pitting corrosion.

In Aluminum 3, blackening occurred only on one side, which may indicate uneven quality. The salt was more piled up on the left side. In a 32X magnification of Aluminum 3 surface seemed unharmed except of a few white pits.

Aluminum 2 exhibited blackening like Aluminum 3 but was uniformly along the sample below the interface. The salt was more piled up on the left side. In a 32X magnification of Aluminum 2, the pitting corrosion was clearly denser than in Aluminum 3, which refers to difference in corrosion behavior due to heat treatment.

Aluminum 4 exhibited blackening significantly less than Aluminum alloys 2 or 3 and the salt precipitate was also on the left. Magnesium content is higher in Aluminum 4 than in Aluminum 2 or 3 which explain the slighter blackening. In a 32X magnification of Aluminum 4, the pitting corrosion was dense but the pits were small.

The color of Aluminum 5 is closer to “before”-state than in Aluminum alloys 2, 3 or 4. The local blackening area was noticeable at the edge. In a 32X magnification picture of Aluminum 5 there occurred dense and large pits (**Figure 25**). According to literature, 5000-series has better corrosion resistance than 6000 and it can be verified because

the pits were the largest and in the shortest distance from each other in Aluminum 5. There was not a lot blackening but as mentioned, it is not an actual corrosion type.

The difference between Aluminum 2 and 3 to Aluminum 5 is that Aluminum 5 contains more silicon and Aluminum 2 and 3 in turn contain almost double the amount of magnesium Aluminum 5 contains. Aluminum 1 also contains significantly less magnesium than Aluminum 2 or 3. On the other hand, there are affecting also other alloying elements and environment to the blackening and corrosion behavior.

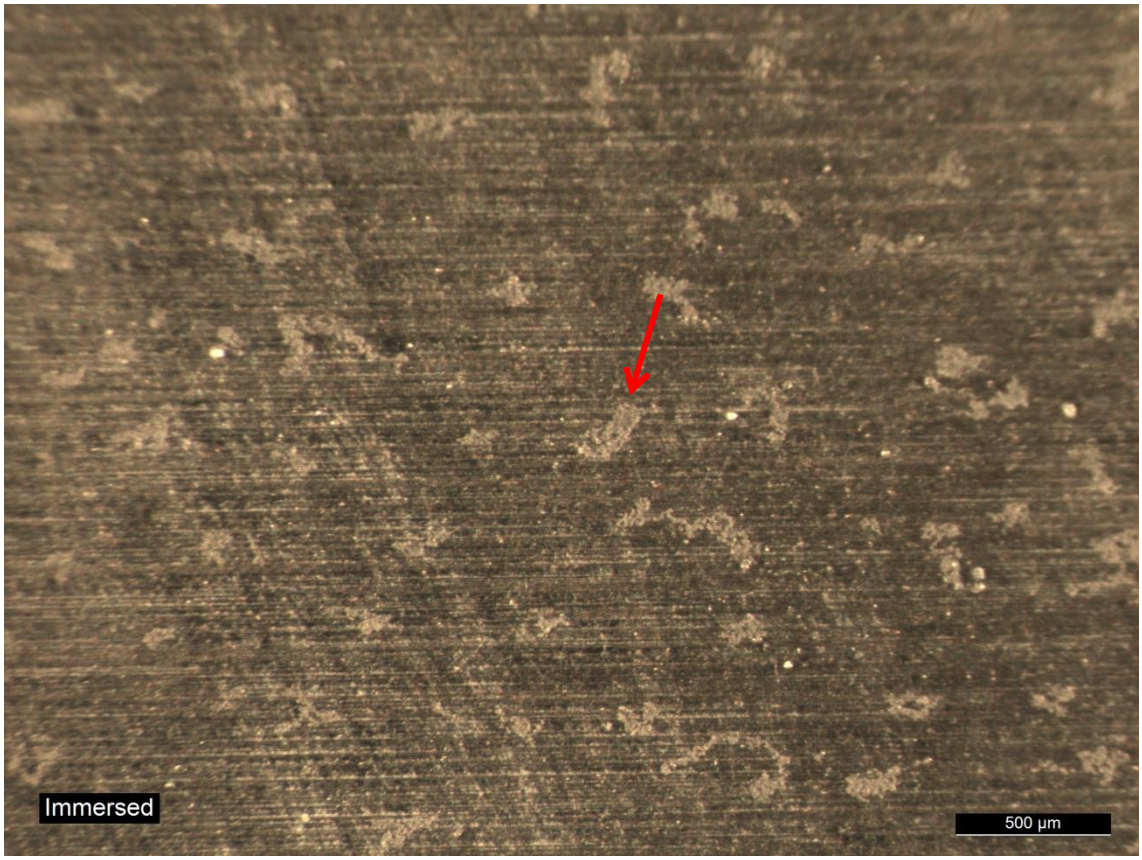

Figure 25. *Stereomicroscope picture of immersed Aluminum 5, 32X magnification. Red arrow indicates an example of pit.*

In Alucobond (alloy 5005), the blackening was very similar to alloy Aluminum 2, but clearly even darker. The clear difference in chemical composition is that Aluminum 2 and 3 contain far more magnesium than 5005. There was not seen any pitting or other corrosion types in 32X magnification of Alucobond.

As mentioned, coated materials excluding Coating 4 and galfan-coated steel were not damaged at all. The anodizing provided good protection for them from corrosion and blackening, because there were not changes in 32X magnification either. In Coating 4 the scratch started to darken (**Figure 24**) and galfan-coated steel showed obvious

changes after the test. The surface was clearly evenly darkened and has salt deposits on it. Galfan included 5% zinc and it is possible that zinc and chlorine formed zinc chloride.

All in all, in corrosion test Coating 2, Coating 1 and Coating 3 as well as Coating 5 and powder coated steel performed the best.

7.1.2 Alkaline environment

Alkaline or highly acidic environment cause uniform corrosion for aluminum alloy, which is due to high solubility of the natural oxide film (discussed in section 7.1.1). The dissolution of the film happens faster than its formation. Phenomenon can be prevented by an appropriate inhibitor. In alkaline environment, sodium silicate decreases the dissolution of oxide film of aluminum alloys. (39)

Figure 26 shows the changes caused by the alkaline environment on uncoated aluminum alloys. Alucobond, Aluminum 3, Aluminum 1 and Aluminum 2 were the most strongly colored by the impact of alkalinity. Aluminum 4 and Aluminum 5 were slightly discolored, the latter hardly at all. Uncoated aluminum samples were examined by stereomicroscope but there were not changes in structures. The results tell about the thicknesses of oxide layers in different alloys: based on this test, the oxidation layer is the thickest on Aluminum 5 and thus it protects it from uniform corrosion.

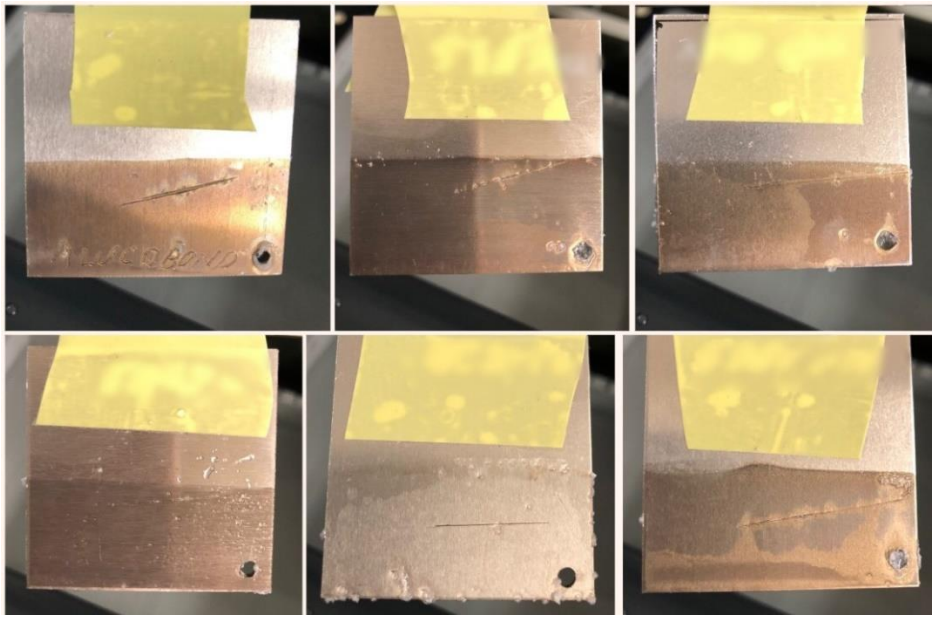

Figure 26. *After 120h alkaline environment test – from left to the right from top to the bottom: Alucobond, Aluminum 3, Aluminum 1, Aluminum 4, Aluminum 5 and Aluminum 2.*

Figure 27 shows coated aluminum alloys and galfan-coated steel. All other endured the alkaline conditions unchanged but galfan-coated steel stained the dark stripes.

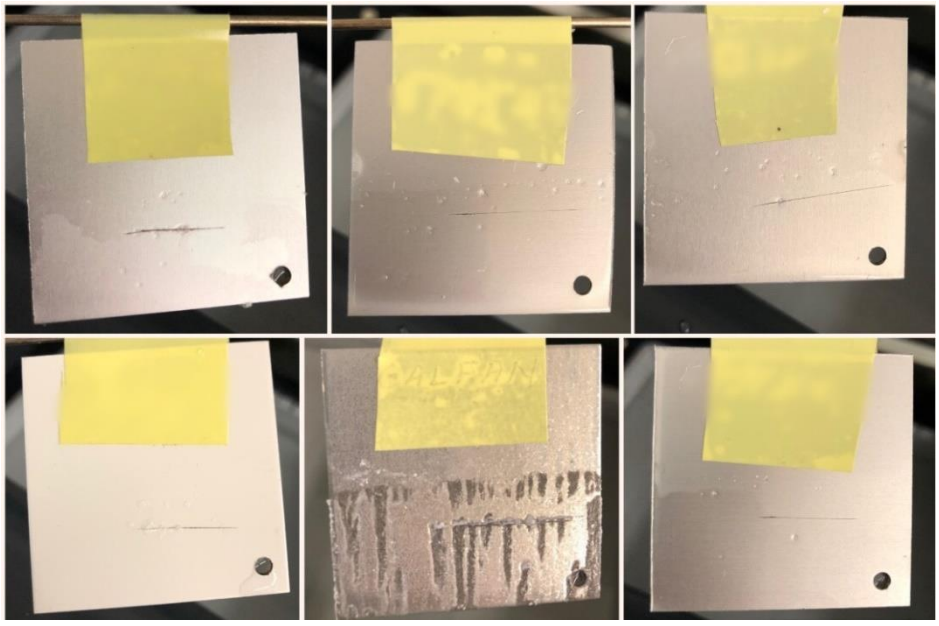

Figure 27. *After 120h pH-test – from left to the right from top to the bottom: Coating 4, Coating 2, Coating 3, Coating 5, galfan-coated steel and Coating 1.*

GFRP, powder coated steel and plastics remained unchanged. All in all, all coated materials excluding galfan-coated steel passed the test as well as all polymers including GFRP did.

7.1.3 Water absorption

Water absorption test results are presented in **Table 5**. Water absorption percent was calculated from equation 1. Each sample was lightened by a few hundred parts due to drying. PE 300, ABS and PE 1000 reached the same weight as before drying whereas GFRP and POM C outweighed the starting weight after 24 h. After 48 hours, POM C and ABS absorbed one hundredth of the extra weight while others remained the same as after 24 h. The increase in the weight of GFRP is explained by the fact that the sides of the samples were unprotected due to cutting, as opposed to the actual use and the glass fibres absorb moisture. Therefore the result of GFRP is not representative. POM C, on the other hand, is homogeneous so the polymer absorbs some moisture to itself. After 48 hours, ABS had the highest water absorption percentage of all test materials excluding GFRP. Test indicated that POM C and ABS have tendency to absorb moisture more than other test materials.

Since the scale gives only one hundredth of a precision, it is not possible to detect all water absorption from the results. Not all materials had water absorption information provided by the supplier, but according to DIN EN ISO 62 the water absorption of POM C is 0.05% after 24 hours and 0.1% after 96 hours at 23 °C. The measured percentage of water absorption for POM C (0.27% after 24 hours) can be explained by the inaccuracy of the scale. In any case, similar measurements and calculated percentages will help to sort the test materials according to their water absorption capacity. As a result, GFRP passes the test because the sample does not encounter reality. Other polymers failed due to differences in masses before and after baking, because all absorbed some moisture.

Table 5. *Results of water absorption test.*

m [g]	GFRP	PE 300	POM C	ABS	PE 1000
Before baking	7.43	7.19	11.11	7.91	7.14
After baking (80°C, 2 hours)	7.40	7.18	11.10	7.89	7.13
After water absorption (23°C, 24 hours)	7.44	7.19	11.13	7.91	7.14
After water absorption (23°C, 48 hours)	7.44	7.19	11.14	7.92	7.14

Water absorption %	GFRP	PE 300	POM C	ABS	PE 1000
After water absorption (23°C, 24 hours)	0.54	0.14	0.27	0.25	0.14
After water absorption (23°C, 48 hours)	0.54	0.14	0.36	0.38	0.14

7.2 Thermal properties

The thermal properties include the materials thermal conductivity and thermal expansion. Thermal expansion is part of dimensional stability determination.

7.2.1 Thermal conductivity

The data collected by the sensors were plotted and a few examples are shown in **Figures 28-31**. Generally speaking, the differences between the three sensors of the polymeric materials were large due to the poor thermal conductivity of plastics, see **Figures 28 and 29**. GFRP although has better thermal conductivity than homogeneous polymer. Metals, on the other hand, conduct very well so the differences between the sensors were small as in **Figure 30**. The difference between coated aluminum and non-coated aluminum was that coating impaired thermal conductivity (**Figure 31**).

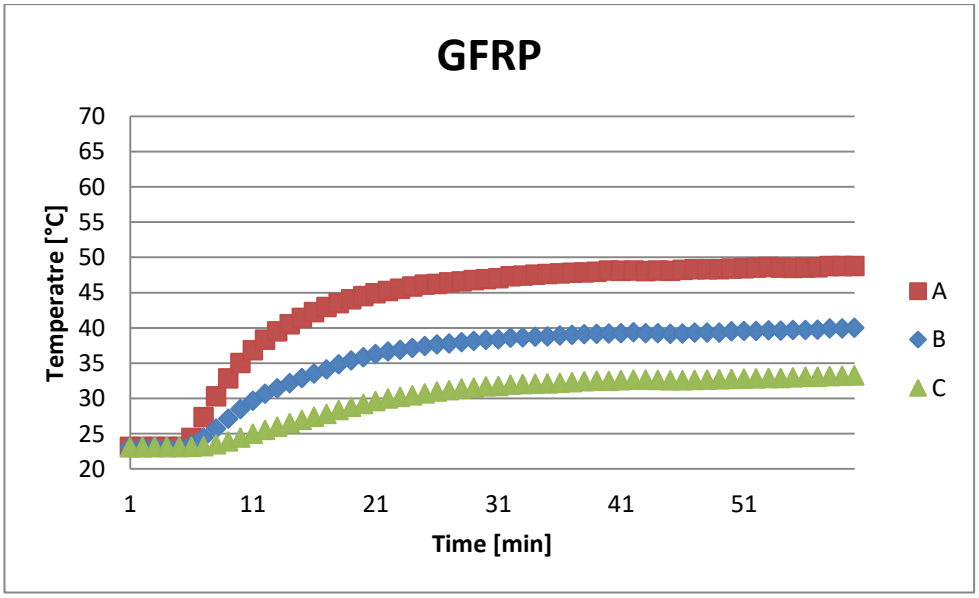

Figure 28. *Chart of the reference material, GFRP.*

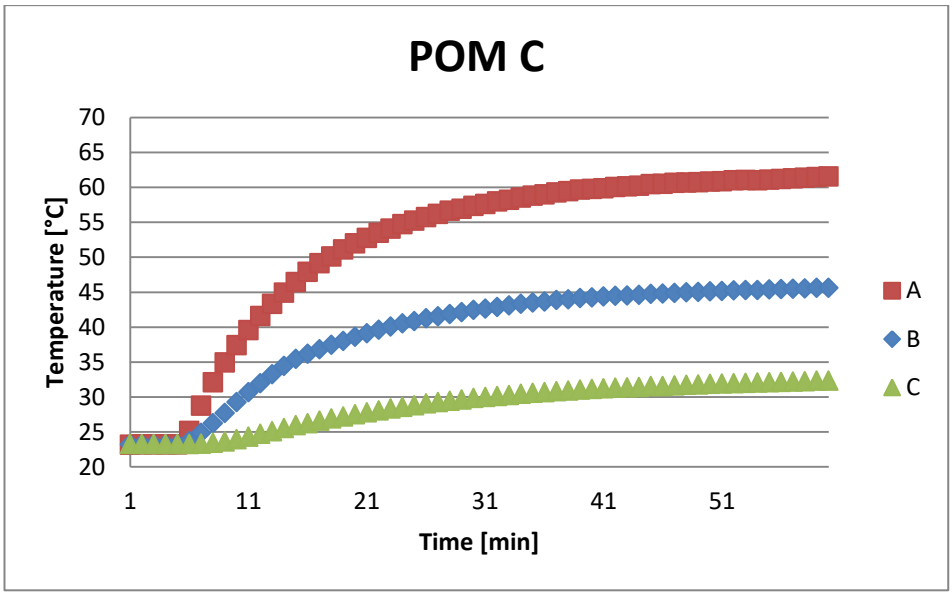

Figure 29. *Chart of POM C as an example of the large differences between sensors in polymers.*

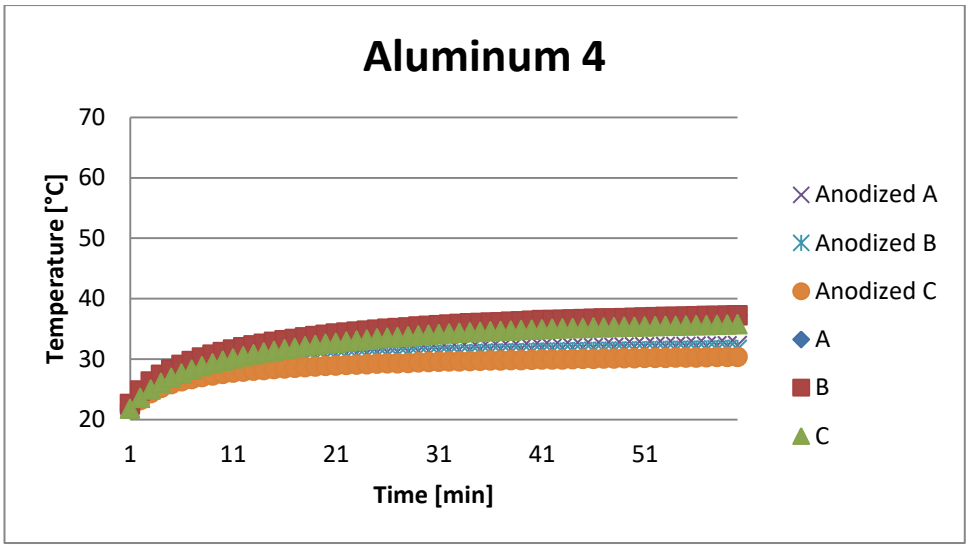

Figure 30. *Chart of Aluminum 4 with and without anodization. Anodization decreases heat conduction.*

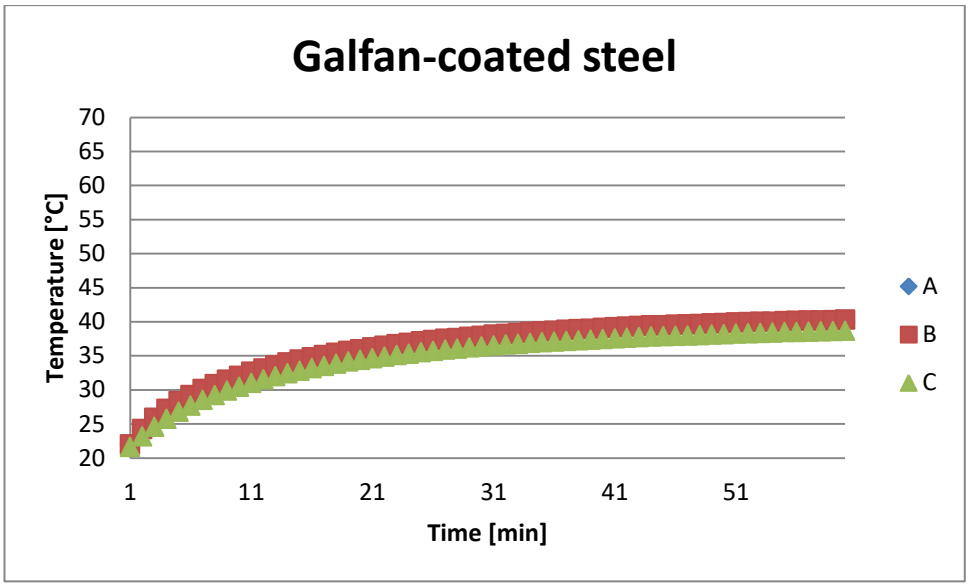

Figure 31. *Chart of galfan-coated steel as an example of coated steel. The differences are small.*

Table 6 lists the maximum values measured by each sensor at a given location. The first column shows the temperature measured by the sensor at the heating wire, which was presumably the highest for the material in question. The highest temperature was reached in ABS, 62,972 °C. The highest local temperatures are visualized in bar chart, **Figure 32**. Other plastics also reached the same temperature range. Metals had lower local temperatures at the sensors because of their good thermal conductivity, which spreads the heat over a wide area compared to plastics. This was reflected in the temperatures measured by the sensors farther away, so that the sensors on the surface of the metals showed almost the same temperature value without significant temperature collapses, but the temperatures of plastics fell even at short distances. The thermal conductivity behavior of GFRP was similar to that of other plastics, albeit with slightly smaller temperature changes. The good thermal conductivity of the metals is thus an advantage, since with fewer thermal wires can be heated over a wider area and thus prevent ice formation during the thawing process at the bottom of the freezer.

Table 6. *Maximum values of thermal conductivity as measured by different sensors. ABS had the highest local value, 62.972 °C.*

	Sensor on thermal wire [°C]	ΔT	Sensor at distance 2.5 cm [°C]	ΔT	Sensor at distance 5.0 cm [°C]
GFRP	48.8	8.8	40.0	6.8	33.3
PE 1000	52.8	16.4	36.4	4.6	31.8
POM C	61.5	15.9	45.6	13.3	32.3
ABS	63.0	22.8	40.2	8.3	31.9
PE 300	57.3	13.3	44.1	12.5	31.5
Coating 4	37.4	1.1	36.2	0.4	35.8
Powder coated steel	40.3	1.5	38.8	2.0	36.8
Alucobond	42.2	0.0	42.1	0.7	41.5
Coating 5	38.6	0.7	38.0	1.5	36.5
Coating 3	32.3	0.7	31.6	1.2	30.4
Coating 1	33.4	0.4	33.0	1.7	31.3
Coating 2	34.5	0.3	34.2	1.8	32.3
Aluminum 5	36.6	-0.3	36.9	1.6	35.3
Aluminum 4	37.2	0.0	37.2	1.5	35.7
Aluminum 2	37.6	-0.9	38.5	1.6	36.9
Galfan coated steel	40.0	-0.3	40.3	1.6	38.7
Aluminum 1	37.2	0.2	36.9	1.3	35.7
Aluminum 3	38.8	0.7	38.1	1.9	36.2

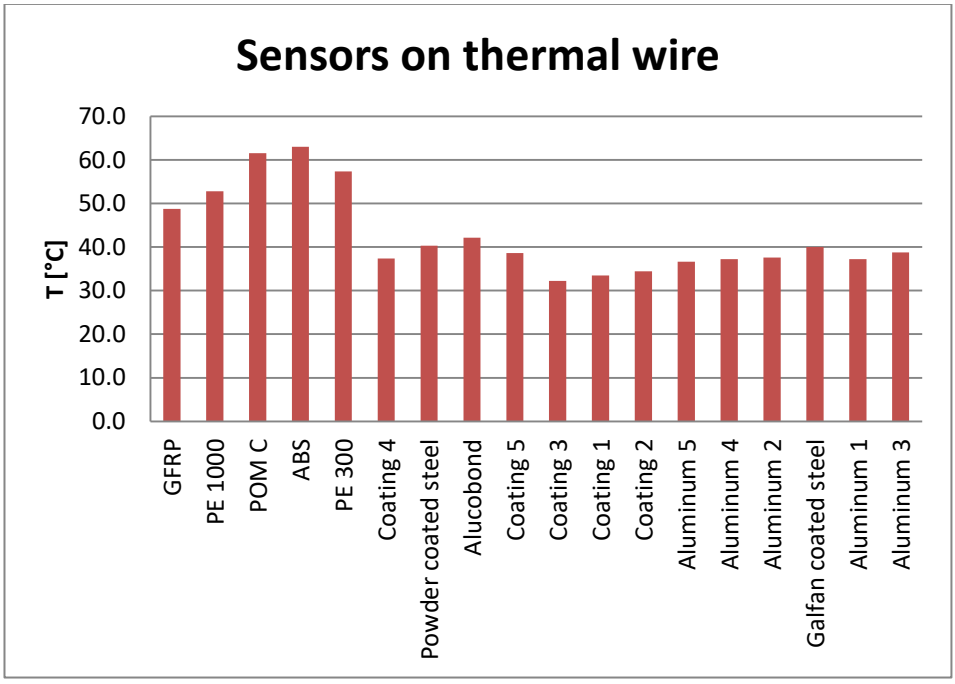

Figure 32. *The highest local temperatures at A-sensors.*

7.2.2 Thermal expansion

Dimensional changes of different materials were calculated from thermal expansion coefficients (**Table 4**) with equation 2 and results are presented in **Table 7**. The thermal expansion of GFRP was measured on a 2500 mm long base.

Table 7. *Dimensional changes due to thermal expansion in temperature range 40 °C, *measured value. Other thermal expansion values of GFRP are calculated from the measured value.*

Length of the base [mm]	1880	2500	3750
PE300	13.5	18.0	27.0
PE1000	15.0	20.0	30.0
ABS	4.9	6.5	9.8
POM C	9.8	13.0	19.5
Aluminum 1	1.7	2.3	3.5
Aluminum 2	1.8	2.4	3.6
Aluminum 3	1.8	2.4	3.6
Aluminum 4	1.8	2.4	3.6
Aluminum 5	1.7	2.3	3.5
Alucobond	1.8	2.4	3.6
Steel	0.9	1.2	1.8
Coating 5	1.8	2.4	3.6
Coating 4	1.5	2.0	3.0
GFRP	3.8	5.0*	7.5

It is obvious that the longer the piece, the greater is the change in length. The length changes of the polymers are up to about eight times that of the aluminum. ABS has exceptionally precise dimensional stability compared to other polymer materials, near to GFRP's. The largest dimensional change is in PE 1000 and the smallest in steel. Dimensional changes due to the thermal expansion must be taken into account when designing the structure. Large thermal expansion also causes a risk that the joint between base and wall material damages and water may leak into polyurethane.

7.3 Mechanical properties

Scratch and impact test were performed mechanical tests and tensile and hardness test results are from literature. Mechanical test were done to all test materials. Generally, test results would be more valid if thicknesses of samples were the same. All materials were not in the best conditions because they had already in delivering little scratches and dirt.

7.3.1 Scratch

In scratch test, all materials were scratched properly, so the test may have been too harsh to get differences between materials. **Figure 33** shows polymers, GFRP and powder coated steel. Visually homogeneous materials looked better scratched than coated because the underlying material was visible under the coating. The surface scratch resistance of a homogeneous material can be improved by patterning, where scratches would be less well distinguished. For a homogeneous material, white is more merciful color than black for scratching if no patterning is used.

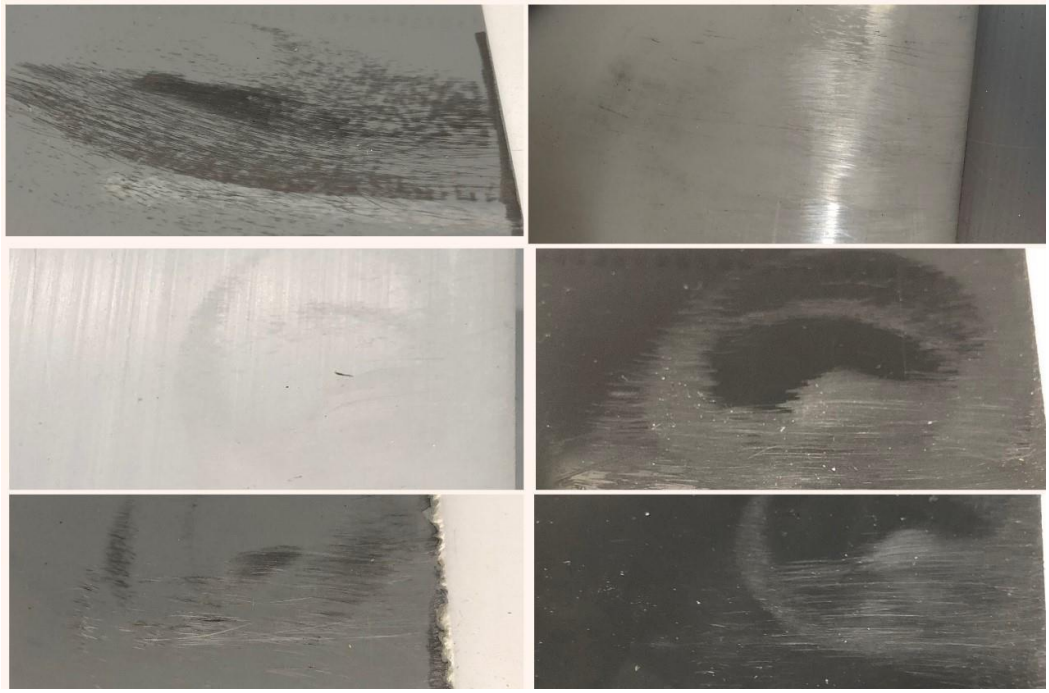

Figure 33. *From left to right from top to bottom: powder coated steel, POM C, PE 1000, PE 300, GFRP and ABS.*

Figure 34 shows the rest of the coated materials. Visually comparing them, it appeared that galfan-coated steel had the least scratches. This may be due to fact the color of the base material did not differ significantly from the color of the coating and that steel is a really hard material compared to others (see section 7.3.4 Hardness). There was not much difference between coated aluminum alloys, but most scratched material of the coated ones seemed to be Coating 5.

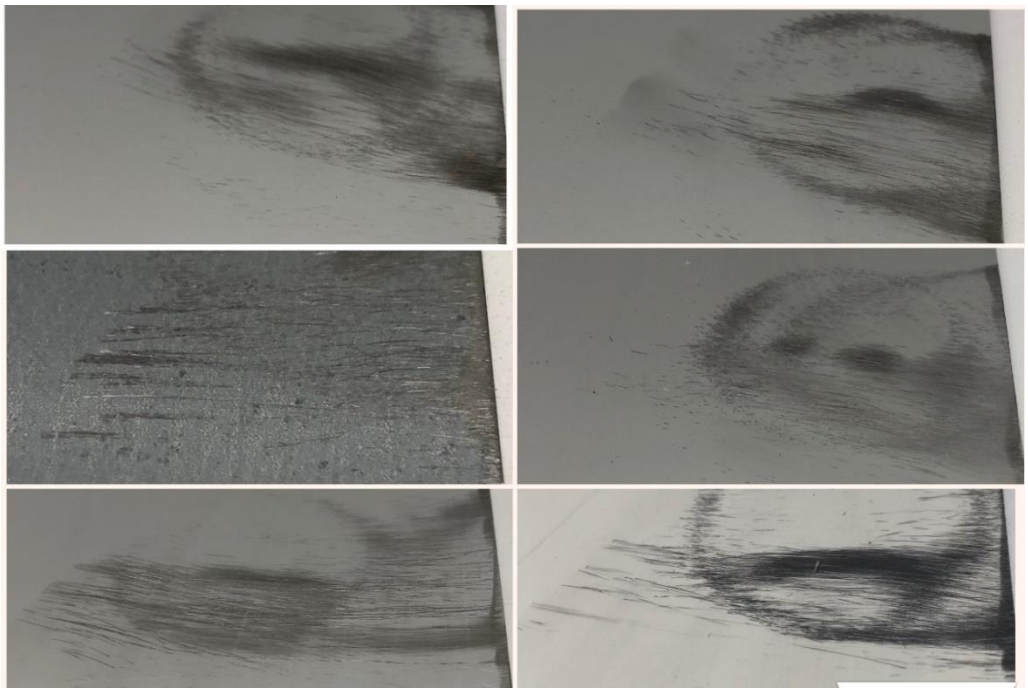

Figure 34. *Coated materials from left to right from top to bottom: Coating 2, Coating 1, galfan-coated steel, Coating 3, Coating 4 and Coating 5.*

Figure 35 shows uncoated aluminum and, as expected, the softness of the aluminum made them susceptible to scratching. Of the uncoated materials, Aluminum 3 appeared to be the least scratched.

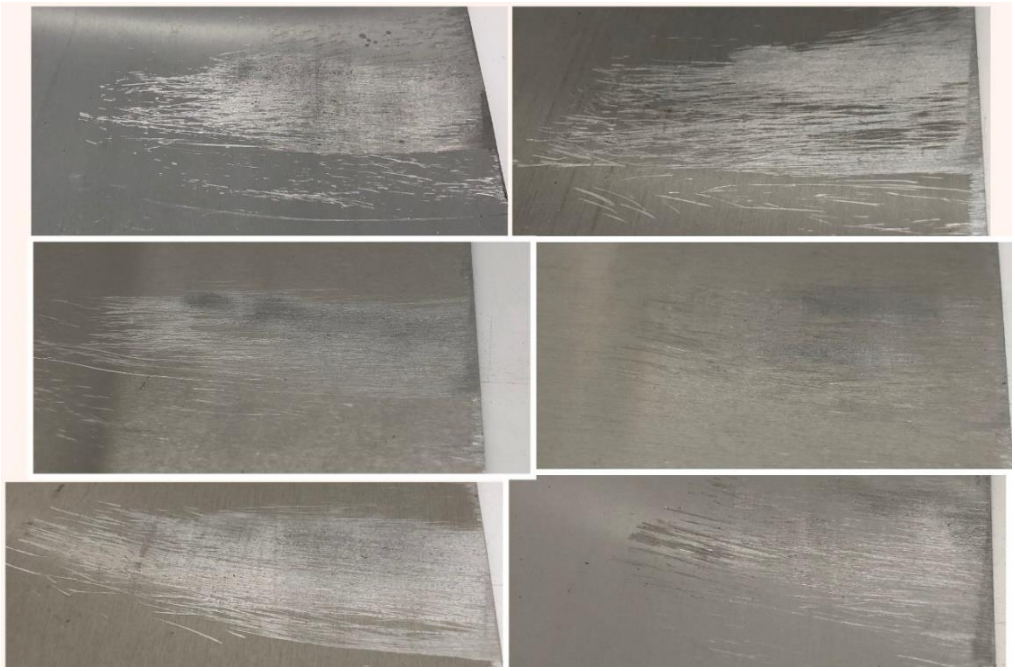

Figure 35. *Plain aluminums from left to right from top to bottom: Alucobond, Aluminum 5, Aluminum 2, Aluminum 3, Aluminum 4 and Aluminum 1.*

The results are not completely comparable and reliable. In the exhibition of materials, different materials had different amounts of surface to be scratched, as it was difficult to

position them so that everyone was exposed to exactly the same amount of force. A glass jar rotating at the end of the shaft might had bounced and exerted more force on one point than another. Material boards were also of varying thickness due to availability. However, the glass jar at the end of the shaft was not locked to a certain height, but was able to move dragging so that its own mass only pressed it against the surfaces of the material.

7.3.2 Impact

As described in chapter 6.2.7, the impact samples were subjected to the impact test at two temperatures, room temperature and -20 °C. The samples had a wide range of thicknesses so the deflection can only be estimated and their comparability is only indicative (see Chapter 6.1 **Table 3** test materials and their thicknesses). Only small differences were observed between some metals with different sample temperatures. On the other hand, plastics had a clear difference in behavior: they were really stiff in the cold and very flexible at room temperature. The deflections of PE 300 are presented in **Figure 36** as an example of temperature behavior of polymers. The greatest change in the different temperature behavior was with POM C, where the difference in deflection between room temperature and cold sample was more than 40 degrees.

It was discussed in chapter 5.1.1 that ABS may be brittle in -20 °C. The test proved differently: ABS was clearly more rigid than in room temperature, but -20 °C was not cold enough to make it crack even though the glass transition temperature is significantly higher.

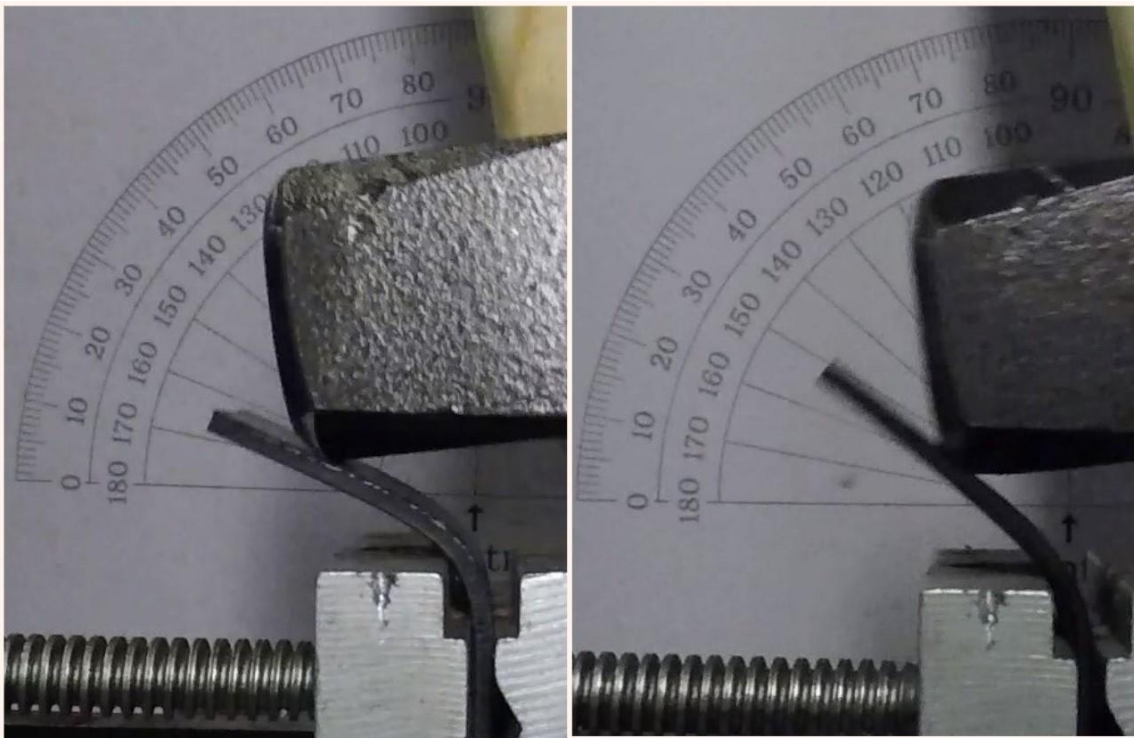

Figure 36. *PE 300, Left: room temperature, right: -20 °C. The difference between the bending angles of the samples was approximately 15 degrees.*

Table 8 shows the elastic and plastic deformation angle and percentage of all test samples at room temperature. As seen in **Table 8**, generally speaking polymers and GFRP had more elastic than plastic deformation. Metals, on the other hand, had a much larger proportion of plastic deformation. This means that, at least in cold forming, it is much more difficult to cause permanent deformation for the plastics than for the metals. On the other hand, if the bottom is struck, the plastics unlikely leave a trace, but the metals go into dents. Not a single material cracked, even in the cold, indicating their suitability for freezer conditions in that point of view. As mentioned in section 4.4., below the glass transition temperature, the behavior of the polymer is brittle. Therefore, one would have expected that the GFRP, PE 1000 or ABS would have cracked brittle in impact test, but apparently behavior was not brittle enough at these temperatures.

Table 8. *Elastic and plastic deformations at room temperature.*

	Initial deflection [°]	Final deflection [°]	Elastic deformation %	Plastic deformation %
GFRP	60	5	92	8
PE 300	75	20	73	27
POM C	50	0	100	0
ABS	60	10	83	17
PE 1000	85	30	65	35
Alucobond	20	20	0	100
Aluminum 1	80	70	13	88
Aluminum 2	80	75	6	94
Aluminum 3	80	70	13	88
Aluminum 4	55	45	18	82
Aluminum 5	50	35	30	70
Coating 1	80	70	13	88
Coating 2	80	70	13	88
Coating 3	45	40	11	89
Coating 4	80	70	13	88
Coating 5	80	70	13	88
Powder coated steel	40	35	13	88
Galfan	15	12	20	80

7.3.3 Tensile

Tensile test results were from supplier or literature except values of GFRP. Its tensile test was performed at Tampere University. Results of GFRP are an average of four tensile tests with similar samples. Results are presented in **Table 9** and average and standard deviation of GFRP's tensile test in **Table 10**. Fracture toughness is calculated by divining maximum load by the original cross-sectional area of the sample. Cross-sectional area is calculated:

$$A_{cross-sectional} = width \cdot thickness = 25\ mm \cdot 2{,}65\ mm = 66{,}25\ mm^2. \quad (7)$$

By utilizing the result of equation 7, fracture toughness is calculated:

$$R_m = \frac{maximum\ load}{A_{cross-sectional}} = \frac{2845{,}2277\ N}{66{,}25\ mm^2} = 42{,}946833 \approx 42{,}95\ \frac{N}{mm^2}. \quad (8)$$

Table 9. *Results of tensile tests (25,30), * measured values, ** calculated value.*

	Fracture toughness Rm [N/mm^2]	0.2% Yield strength Rp 0.2 N/mm^2 min.	Elongation at break A50 mm % min.	Young's modulus [MPa]	Tensile strength [MPa]
GFRP	42.95**	12.02*	2.05*	5659.41*	48.39*
Aluminum 1	140 - 180	120	2	70 000	180
Aluminum 2	190 - 240	80	12 - 18	70 000	160 - 200
Aluminum 3	220 - 270	134	15.3	70 000	223
Aluminum 4	275 - 350	150	22.2	71 000	278
Aluminum 5	310	260	6 - 10	70 000	310
PE 300	N/A	23 %	9	900	22
PE 1000	>25 %	-	N/A	>950	27
ABS	55 %	33 %	>2	1900	33
POM C	43 %	32 %	9	3600	80
Alucobond	-	-	>5	70 000	>130
Coating 4	145 - 185	120	2	68 000	160
Coating 5	184	155	9	-	-
Steel	-	-	15	200 000	350

Table 10. *Average and standard deviation of GFRP's tensile test.*

	Average	Standard deviation
Modulus (MPa)	5659.41	39.31
Stress at 0.2% strain (MPa)	12.02	0.56
Tensile strength (MPa)	48.39	3.82
Elongation at break (%)	2.05	0.29

The bar chart in **Figure 37** shows that carbon steel has the highest tensile strength. Different aluminum alloys also have high strengths. The tensile strengths of plastics are generally in the same range than GFRP's.

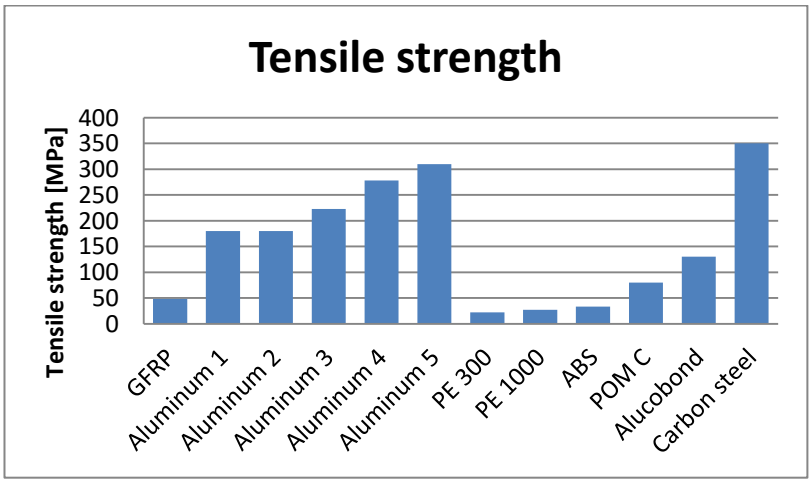

Figure 37. *Differences between tensile strengths of test materials (25,30).*

Engineering stress and strain of GFRP are presented in **Figure 38**. Engineering values do not include the change in cross-sectional area during tensile test whereas true stress and strain (**Figure 39**) do. True stress and strain are calculated with equations 5 and 6 which are in chapter 6.3.1. The tensile test charts visualize the situation where the fibres broke down as the stress increased. The differences between engineering and true values are not significant, probably due to nature of composite material.

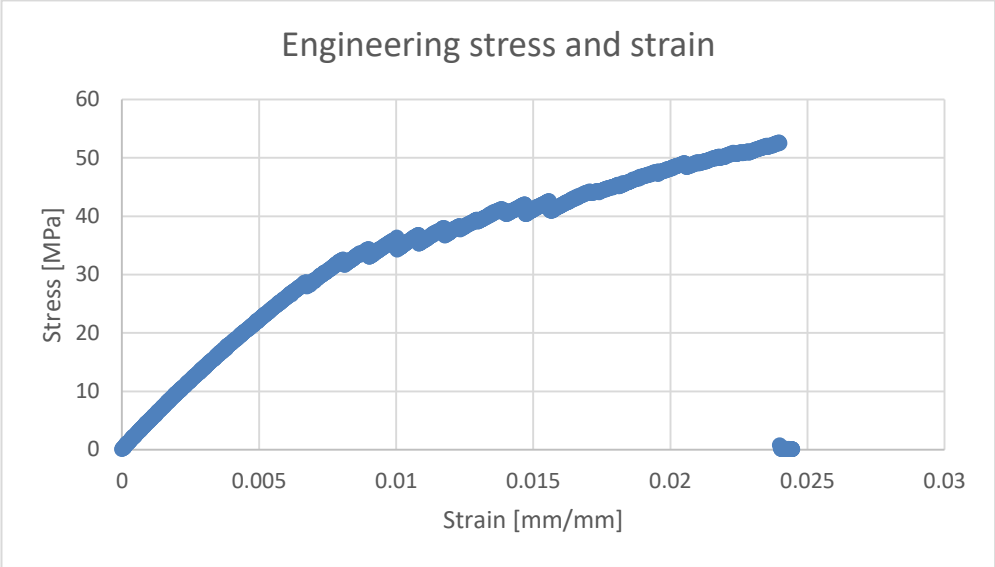

Figure 38. *Engineering stress and strain of GFRP.*

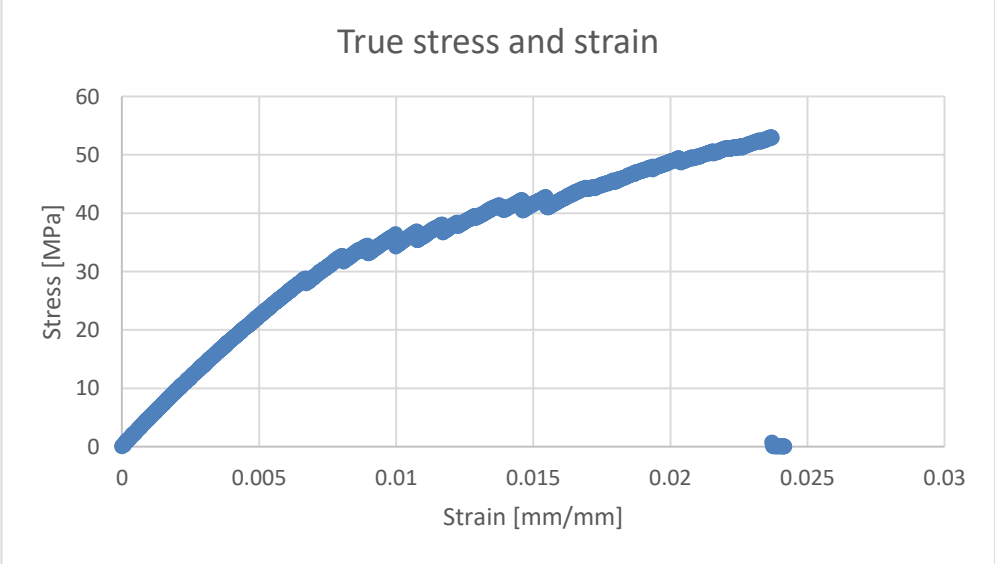

Figure 39. *True stress and strain of GFRP.*

7.3.4 Hardness

Brinell hardness values of the test materials are shown as a bar graph in **Figure 40**. The values are information from material suppliers. By far the hardest materials from

the test materials are POM C and steel. The softest ones are both grades of polyethylene of different densities. These clear differences in the hardness of the materials are also reflected in the results of the scratch test, as discussed in chapter 7.3.1. The harder the material, the less scratching is caused. The impact of anodization is not seen in Brinell hardness test results.

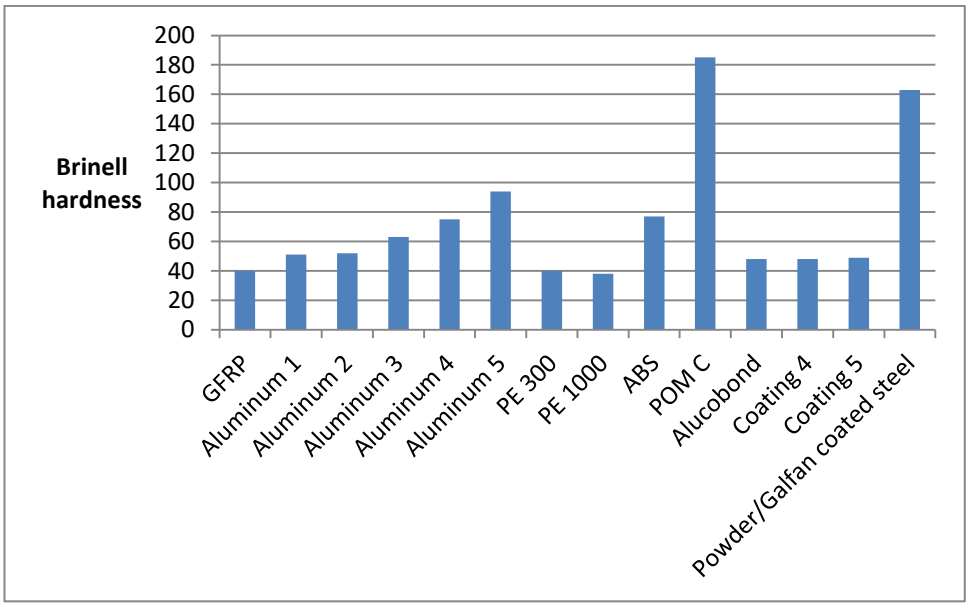

Figure 40. *Brinell hardness chart of test materials (25)(30).*

7.4 Methods to compare materials properties

There are different methods to compare materials' properties and their performance. Truth table evaluates the performance of test materials in tests in a simple way: passed or failed. Weight coefficient method gives a numerical evaluation of each material based on performed test with the help of truth table and also assesses the material comprehensively. The criticality of the property has weight coefficient which multiplies test performance grade.

7.4.1 Truth table

Truth table is one way to evaluate the most suitable materials based on properties. The idea is simple: if property is good enough for the application (GFRP used as a reference) or better it has green box in a column of material. If not, it is red. Finally when all properties of all materials are evaluated it is observed which material has passed the table without red boxes. The end of the summary is marked with red if the material receives any red boxes and green if all are green. The method has drawbacks: if all materials are initially selected to meet the critical requirements well, as there is little difference. On the other hand, the method is indicative and works reasonably well in the ini-

tial material qualifiers. In this case, it is way to present the results of test in criteria fail or pass. The more the criteria are tightened, the better the differences between materials will be. (41)

Truth tables are shown in **Tables 11** and **12** and they are divided in poor and the best performed materials. There is yellow box in the scratching test, because as discussed in chapter 7.3.1, the clear differences are hard to get due to harshness of the test. According to tables, there are six materials which have passed all the tests: Coating 2, Coating 3, and Coating 1 as well as powder coated steel, Coating 5 and Coating 4. Plain aluminum alloys Aluminum 3, Aluminum 4 and Aluminum 2 are not in the table themselves, because they were tested to see how they act without anodizing and what happens if anodization is damaged.

Table 11. *Truth table of the poorly performed materials + reference.*

Requirements/properties	Materials								
	GFRP	PE300	PE1000	ABS	POM C	Alucobond	Aluminum 5	Aluminum 1	Galfan coated steel
Corrosion resistance									
Water absorption									
Alkaline environment									
Thermal conductivity									
Thermal expansion									
Scratching resistance									
Impact strength									
Tensile strength									
Hardness									
Summary									

Table 12. *Truth table of the best performed materials + reference.*

Requirements/properties	GFRP	Coating 2	Coating 3	Coating 1	Powder coated steel	Coating 5	Coating 4
Corrosion resistance							
Water absorption							
Alkaline environment							
Thermal conductivity							
Thermal expansion							
Scratching resistance							
Impact strength							
Tensile strength							
Hardness							
Summary							

7.4.2 Weight coefficient method

In weight coefficient method the materials are numerically evaluated (1=poor … 5=excellent) based on their properties and the properties are also emphasized by the importance of them in this application. For example, “excellent” means excellent in this research, not in the scale of all materials of the world. The criticality of property is also in scale 1-5, and this grade is used as coefficient. The coefficient is multiplied by the success of a given material in a given property, and these multiplied values are summed for a given material to give the material a total score. For example, PE 1000 has grade 5 in corrosion resistance. Corrosion resistance has grade 5 as a criticality of property. Calculation five times five produces 25. PE 1000 has grade 3 in surface quality and criticality of surface quality is 4. They are multiplied and the result is 12. These results are summed 25 + 12 = 37 and added to materials total score.

The determination of the grades to materials criticality is evaluated by considering the importance of the feature in the application. The determination of the materials success in properties is estimated from numerical values if possible such as thermal expansion coefficients in dimensional accuracy. The thermal expansion coefficients of the material alternatives are scaled from one to five relative to each other. Every property of materials is not possible to determine based on numerical values. In these cases the success of material is estimated how in literature materials are described compared to each other. The most important thing is to get the material alternatives ranked above each

other because they are already selected from a huge list of materials. When the summarization of points the best material option is seen on the bases of score. (8)

With the help of grades and coefficients radar charts are drawn. They are very visual objects to show in which area certain materials are better than other and where not. It is easier to read a graph when there is only a few materials in one graph, otherwise the material lines may overlap. **Figure 41** lists all material options and compares the current material (values from **Table 13** and **14**), and there are in **Figure 42** the best five materials based on the weight coefficient method and GFRP as a reference (values from **Table 14** only).

Table 13. *Material-specific points determined by weight factor, worst-rated materials + GFRP.*

1=POOR ... 5=EXCELLENT											
Property	**Criticality of property**	GFRP	PE 300	PE 1000	ABS	POM -C	Alucobond	Aluminum 5	Aluminum 1	Galfan coated steel	Coating 4
Excellent corrosion/chemical resistance	**5**	5	5	5	5	5	1	3	3	2	4
Excellent surface quality	**4**	4	2	3	3	4	3	3	3	2	5
Excellent dimensional accuracy	**3**	4	1	1	4	3	5	5	5	5	5
Excellent toughness	**3**	2	1	1	1	2	3	4	4	5	4
Excellent hardness	**3**	3	2	2	3	5	3	3	3	5	3
High thermal conductivity	**2**	3	2	2	1	2	5	5	5	5	4
Weight coefficient		**74**	**49**	**53**	**63**	**75**	**60**	**73**	**73**	**73**	**84**

The criticality of the properties is evaluated so that the higher the criticality factor, the more important the characteristic. For example, the material selected must have a very good corrosion resistance in order that it can be selected as a new material. For another example, toughness is not as important as corrosion resistance because toughness can be affected, e.g., by various shapes or material thicknesses. The corrosion resistance cannot be influenced because different coating options are included as separate options. Thus, the criticality factor is affected by whether there is anything to enhance the property. If there is, the criticality factor is lower, but if not, the criticality is

emphasized. On the other hand, one property is just not as critical to the applications as another. Properties are discussed in chapter 4.

Table 14. *Material-specific points determined by weight factor, best scored materials + GFRP.*

1=POOR ... 5=EXCELLENT							
Property	**Criticality of property**	GFRP	Coating 2	Coating 3	Coating 1	Powder coated steel	Coating 5
Excellent corrosion/chemical resistance	**5**	5	4	4	4	4	4
Excellent surface quality	**4**	4	5	5	5	5	5
Excellent dimensional accuracy	**3**	4	5	5	5	5	5
Excellent toughness	**3**	2	4	4	4	5	4
Excellent hardness	**3**	3	3	3	3	5	3
High thermal conductivity	**2**	3	5	5	5	4	5
Weight coefficient		**74**	**86**	**86**	**86**	**93**	**86**

Corrosion evaluation is specific: those alloys which were ordered also coated are not as uncoated in the evaluation because they were ordered to examine what is the impact of anodization. An advantage is if the uncoated sample resists corrosion well because then it would not be catastrophic if the anodization got damaged. Good performance of uncoated sample increases points and vice versa. 3000- and 6000-series alloys were not coated so they were tested as such. On the grounds of visual evaluation, uncoated aluminum alloys from the best to the worst: Aluminum 5, Aluminum 1, Aluminum 4, Aluminum 3, Aluminum 2 and Alucobond. Stereomicroscope pictures although influence on the final order. Blacking is a visible problem which is seen as a bigger thread than pitting corrosion, because as discussed in chapter 7.1.1, appearance of pits does not mean that they would grow and deepen in the usage time of the freezer. Therefore the major blacking in Alucobond makes it the worst choice.

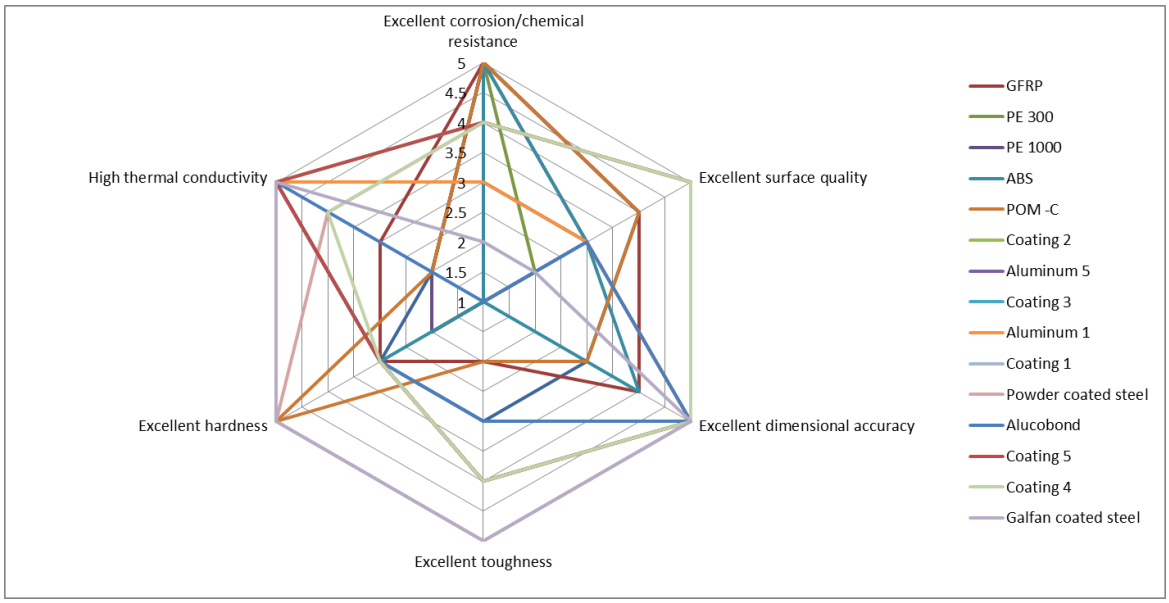

Figure 41. *All test materials presented in radar chart to visualize their performance.*

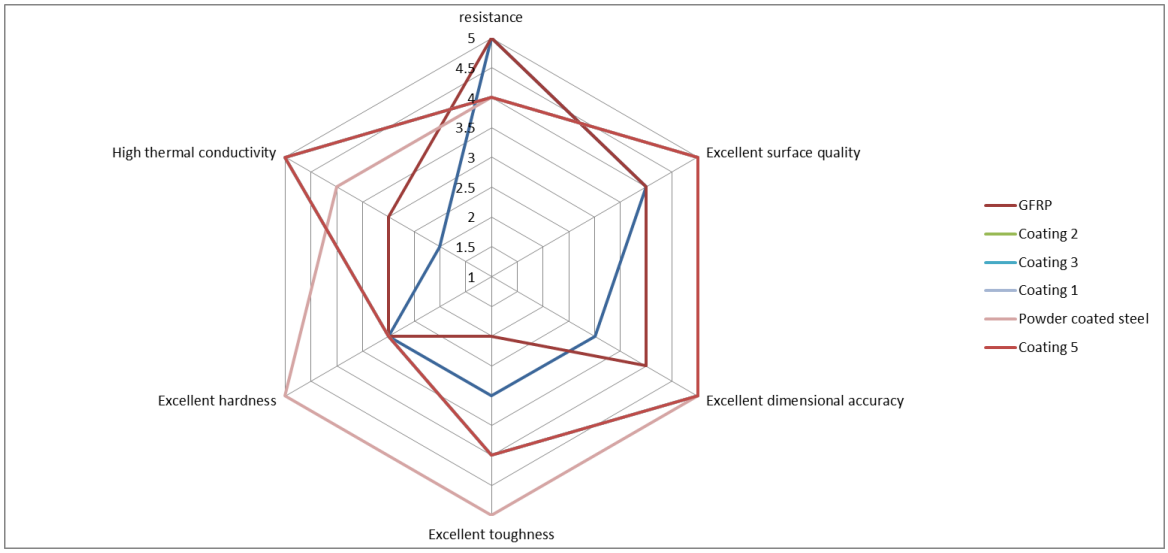

Figure 42. *The best five materials according to the weight coefficient method and GFRP as a reference.*

7.5 Summary

Seven different tests were executed and results of two tests are from literature and university. Corrosion test was done to coated and uncoated metals. The major observations after test were blacking and pitting corrosion in uncoated aluminum alloys. Generally coated materials excluding galfan-coated steel performed well. It was verified that 5000-series aluminum alloys have better corrosion resistance than 6000-series, because the occurred pits were smaller and sparser in the former than in the latter. It was stated that blacking is seen the major problem compared to pitting, because aes-

thetically blacking harms more in this application. According to corrosion test results it can be said that Coating 3 survived the best, because it was not damaged at all as coated and plain alloy survived also well in comparison.

Water absorption test was performed for polymer materials and GFRP. Excess moisture was removed from all of them before water immersion and they were weighed. The samples were weighed after 24 and 48 hours. PE 300 and PE 1000 gained exactly the same weight than before moisture removal thus they did not swell. POM C, ABS and GFRP gained more weight than in the beginning but GFRP has cut edges and therefore water immersed in glass fibres. It is also possible that epoxy matrix immersed slightly water. None of the materials immersed hazardous amount of moisture.

Alkaline environment test was done to all test materials. Broadly, polymers and coated materials excluding Galfan-coating performed the best in the test. In comparison of plain aluminum alloys, the best performed alloy was Aluminum 5 and the second best Aluminum 4. This test segregates Aluminum 4 from other same series alloys distinctly.

Thermal conductivity test was performed to all test materials. Polymers have poor thermal conductivity and the heat did not spread uniformly on them. The local heating was the highest with ABS. Metals did not gain as high local temperatures as polymers but the difference between sensors was negligible. The heated area was a lot wider with metals than polymers. Anodization decreased the conducted heat but heat was still spread widely and uniformly. Powder coating caused difference between sensors so the heat distribution was uneven. It was surprising that PE-layer in Alucobond did not prevent heat to conduct evenly. As a conclusion, the more stable the heat conduction is, the better because then less amount of heat wires are needed. GFRP has poor heat conductivity but homogeneous polymers even worse.

Thermal expansion of GFRP was 5 mm in 2.5 m base. All metal materials expanded half less of that, steel only a quarter. Polymers expanded relatively much, ABS the least and its expansion was near to GFRP's (6.5 mm). PE 1000 expanded even 20 mm and with such expansions there should be made changes in design. It has been difficult already with GFRP so it is not recommended to accept larger expansions. Even though, with shorter bases polymers could work.

Generally, scratch test was harsh to all materials. Harshness is due to hardness of glass, which is relatively higher than hardness of any test material. The test situation

does not correspond to reality and probably glass as a scratching material was not the best selection. It can be said that esthetically homogeneous materials did not suffer from scratching as much coated did. The reason is that the basic material has different color than the coating, so it is highlighted when coating is damaged. Homogeneous materials do not have that problem. Galfan-coated steel suffered least from the scratching because it is hard compared to aluminum alloys and polymers and galfan is almost the same colored than steel. From coated aluminum alloys Coating 5 seemed to be scratched the most: the contrast between white coating and dark basic material is large. Uncoated aluminum alloys scratched a lot which was expected due to softness of aluminum. They were tested to notice significance of anodization and also therefore that differences between aluminum series would be seen, which is unfortunately difficult to see.

Impact strength of metals did not change with cold samples nearly at all. There were tiny differences, but it can also be due to camera properties, because if the frame picture density was not high enough the maximum position may not be seen. Polymers did have clear differences between room temperature and cold behavior: in the former they were flexible and in the latter more rigid. The largest difference was with POM C: over 40 degrees difference in deflection angle. It was possible to determine partitions of elastic and plastic deformation from impact videos and it was done samples which were tested at room temperature. Deformation of plastics was mostly elastic and metals in turn had plastic deformation. Alucobond was the only material without any elastic deformation. Results would be more truthful if all samples had same thickness but it was not possible due to availability. Results indicated that cold-forming is a lot easier with metals than polymers but on the other hand in the event of impact polymers will recover better than metals. None of the materials cracked which is positive.

Tensile test results were compared to get differences in mechanical properties. According to the tensile test which was performed at Tampere University, the tensile strength of GFRP is relatively low. It is approximately at the same level as other polymers'. Judging by this, all metals and POM C have higher toughness which is beneficial for application. The initial situation with GFRP is low, so selecting of any metal makes the situation better in that point of view.

Brinell hardness test results highlight two over other: POM C and powder or galfan-coated steel. From aluminum alloys Aluminum 5 is the hardest and other alloys are quite equal. Comparing these results to the scratching test results, the hardness of

steel distinguished but POM C was not particularly well performed. As pointed out, scratch test was harsh and in real situation POM C and coated steels would probably remain in good condition.

According to the test results, weight coefficient method (**Table 14 and 15**) and truth tables (**Table 12 and 13**) the best five of all test materials are powder coated steel (93 points), Coating 5 (86 points), Coating 2 (86 points), Coating 1 (86 points) and Coating 3 (86 points). They all got the green line in truth table comparison and got the highest points. There are not clear differences to rate materials that got 86 points. One way is to consider scratching test, even though the test was harsh to all materials. As mentioned, Coating 5 seemed to be scratched the most of the coated materials. On the other hand, all coated materials were scratched fairly so it has to be considered does the test correspond to the reality or should the scratching be tested in some other way. If it corresponds to the reality, thicker hard-anodizing could be better option. Powder coated steel was also clearly scratched and the threat with it is that if the basic material, steel, is visible under the coating it would definitely get corroded. It has to be 100% sure that the powder coating remains unchanged. From that point of view coated aluminum is more safe solution because aluminum is intrinsically corrosion resistant and it would not cause as much harm if the anodization is damaged.

If it is wanted to get difference between coated aluminum alloys, it has to be done by comparison of the test results by looking closely. The weight coefficient method and the truth table based on categorizing materials to the scale 1-5. Coated aluminum alloys were in the same category so the points and performance looked the same. When looking at the performance of materials from test to test, one rises above the other. In corrosion test, by visual evaluation the order of uncoated alloys of these three is from the best to the worst: Aluminum 4, Aluminum 3 and Aluminum 2. In alkaline environment test the same materials are in order: Aluminum 4 and the last two Aluminum 2 and Aluminum 3 are equally bad. In thermal conduction test Aluminum 3 and Aluminum 2 succeed better than Aluminum 4 but it is due to that Aluminum 4 is 1.5 mm thick and Aluminum alloys 2 and 3 1.0 mm thick. In thermal expansion Aluminum 2 and 3 expanded less but the difference to Aluminum 4 is only 0.01 mm in 2.5 m long base. In scratching test by visual evaluation Coating 3 seemed to be slightly less scratched than Coating 2 and 1. In uncoated case the difference is impossible to say. In addition, Aluminum 4 has better tensile strength and higher hardness than Aluminum 3 or 2. Based on this comparison, the Coating 3 emerged as the best choice from test materials.

8. CONCLUSIONS

Motivation to execute this research was a need to get rid of disadvantages of Glass Fibre Reinforced Polymer (GFRP) composites in remote freezer structure. Disadvantages are poor cost-effectiveness, harmfulness for people and environment, slow and inaccurate manufacturing, poor recyclability and lack of optimization.

GFRP has also beneficial properties: resistance to temperature fluctuations that occur in freezer conditions, great corrosion and chemical resistance, good surface quality and mechanical properties with lightweight structure. GFRP was used as a reference in consideration of new solution but it was also thought what is optimal for the certain conditions including manufacturing and usage. After determination of essential properties material property charts were utilized. The limit for rejection was not strict because there was not existing absolute right answer or numerical value. Price and availability criteria eliminated before sample order too expensive or extraordinary materials. Test arrangements were designed to measure desired material properties.

Coated aluminum came up from test materials as the most considerable option, especially Coating 3. From different aluminum alloys it was expected that Coating 3 would represent the best aluminum series due to high corrosion resistance. In addition, coating was also expected to enhance chemical resistance. Polymers excluded themselves in thermal expansion test, because the expansions of them were even large compared to current material, which was predictable. Also their water absorption might be risk in dimensional stability. Polymers are although potential options in shorter components, where the thermal expansion would not be as significant. Disadvantage of coated steels is that it cannot be said with 100% reliability, that the coating endures and protects steel from corrosion. In comparison between aluminum alloys and their coated versions, Coating 3 showed that it fulfils requirements best and plain aluminum without coating also endure some chemical load.

In order to promote the project, the following points should be considered. The optimal thickness of the base has to be determined and re-evaluate if the used coating is sufficient to prevent aluminum from scratching in real freezer conditions. The formability of

the material is one of the subjects of the research to determine whether the material fulfill the design forms of the current product. For example, if the meltwater gutter cannot be made current with this material, consideration should be given to redesigning the base profile.

In the introduction was said that the aim of this thesis is to replace GFRP and there are several disadvantages of it. Suggestion is made under certain conditions. What are the advantages of Coating 3 compared to GFRP? GFRP was said not to be cost-effective. It cannot yet be said is Coating 3 either, but production of aluminum is so enormous that in volumes of freezer production the price is possible to get in reasonable level.

GFRP is said to be very hard to recycle or even impossible. Aluminum beats that because it is 95-98 % recyclable material. GFRP's harmfulness for people is highlighted in manufacturing process, where manufacturers are prone to process chemicals. Aluminum production causes also injurious effects for workers but as a ready product aluminum is safe. For example if GFRP is drilled it causes detrimental glass dust which remains in lungs.

As noticed, inaccuracy of manufacturing the product is fixed by aluminum because its thermal expansion is remarkably lower than GFRP's. Aluminum is also better from its thermal conductivity properties and amount of thermal wires can be decreased with it. In addition GFRP might absorb some water, which is not unfortunately sure basing on the executed water absorption test due to cut edges of the GFRP sample.

Aluminum has these improvements compared to GFRP without eliminating advantages of GFRP: it has resistance to temperature fluctuations, good corrosion and chemical resistance, good surface quality and great mechanical properties despite of lightweight. Based on research and test results it can be said that aluminum is more optimized material solution as a remote freezer base material than GFRP.

These results may be utilized in other components of freezers, either in remote or plug-in ones. As discussed in chapter 3, GFRP is ordinary material in boat industry and due to advantages of aluminum; aluminum has partially replaced GFRP in that industry – so why not in this application too.

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APPENDIX A: REJECTED MATERIALS

REJECTED MATERIALS

There are listed fairly potential materials for this application with a simple reason why they have not been selected as a test material. There are also listed some larger entities and it is not existing an unequivocal reason for rejection. It is impossible to list materials and all their alloys of the world not to mention all possible surface modifications and coatings. Test materials are selected based on author's knowledge, literature and suppliers' advisory.

In APPENDIX B, there are charts from CES-guide (42). They have been used to ease rough comparison between materials and to narrow the material candidates.

Metals

Pure Iron

Cast irons

Carbon steels

Stainless steels

Too high performance, aim to find optimized solution

High-Strength Low-Alloy steels (HSLA)

Ultrahigh –strength steels

Tool and machining steels

Maraging steels

Iron-based superalloys

Iron powders

Nickel and nickel alloys

Poor corrosion resistance

Cobalt and cobalt alloys

Manganese and manganese-based alloys

Aluminum and aluminum alloys 1000, 2000, 4000, and 7000

Lack of corrosion resistance

Copper and copper alloys

Zinc and zinc alloys

Lead and lead alloys

Tin and tin alloys

Alkali metals: Li, Na, K, Rb, Cs, Fr

High reactivity, soft

Alkaline earth metals: Be, Mg, Ca, Sr, Ba, Ra

Refractory metals

(16)

Plastics

Polystyrene (PS)

Poor mechanical properties, narrow usage temperature range

Polycarbonate (PC)

Not resistant to solvents

Low density polyethylene (LDPE)

Low mechanical properties

Poly (methyl methacrylate) (PMMA)

Fragile, prone to scratching, low melting temperature

Polyethylene terephthalate (PET)

The lowest usage temperature -20 °C and near vaporizer it can be -25 °C

Polypropylene (PP)

Low mechanical properties, not suitable for freezer temperatures

Polyurethane (PUR)

Too flexible, limited chemical resistance, suitable for tremor attenuation

Polyvinyl chloride (PVC)

Fragile in freezer conditions

Polytetrafluoroethylene (PTFE)

Polyamide (PA)

Poor dimensional stability due to high water absorption

Ceramics, refractories and glasses

Too brittle

Coatings

Cadmium coating

Banned due to its toxic nature and strict environmental regulations (43)

Polypyrrole coating

Poor mechanical and thermal stability in harsh climate conditions

Oil-based coatings with lead and chromium pigments

Illegal

Pure aluminum

Not strength enough

Tin-chromium coating

Magnelis

Used with stainless steels

One-coat epoxy coating with DPP/titanium dioxide/zinc oxide pigments

Three-coat moisture-cure urethane (MCU)

Zinc-rich primers in three coat systems

PAS two-coat systems, second generation

Vinyl-based intermediates and topcoats

Galvalume

Not in alkaline environment

Zinc nickel coating

Difficult to control Zn-Ni electroplating (increases cost)

Sol-gel coating ZrO_2, SiO_2, Al_2O_3

Internal stress causes cracks, long drying times, relatively new technology

<u>Composites</u>

Nanofibre reinforced composite

Relatively very high price

Kenaf fibre reinforced composite

Relatively high price

Ramie fibre reinforced composite

Relatively high price

Sisal fibre reinforced composite

Relatively high price

Aramid fibre reinforced composite

Relatively high price

Carbon fibre reinforced composite

Relatively high price
(8)

Coir reinforced composite

Poor mechanical properties

Natural fibre reinforced composites

Biodegradable, uneven quality which depends on growing environment, poor availability, water absorption

APPENDIX B: MATERIAL SELECTION CHARTS

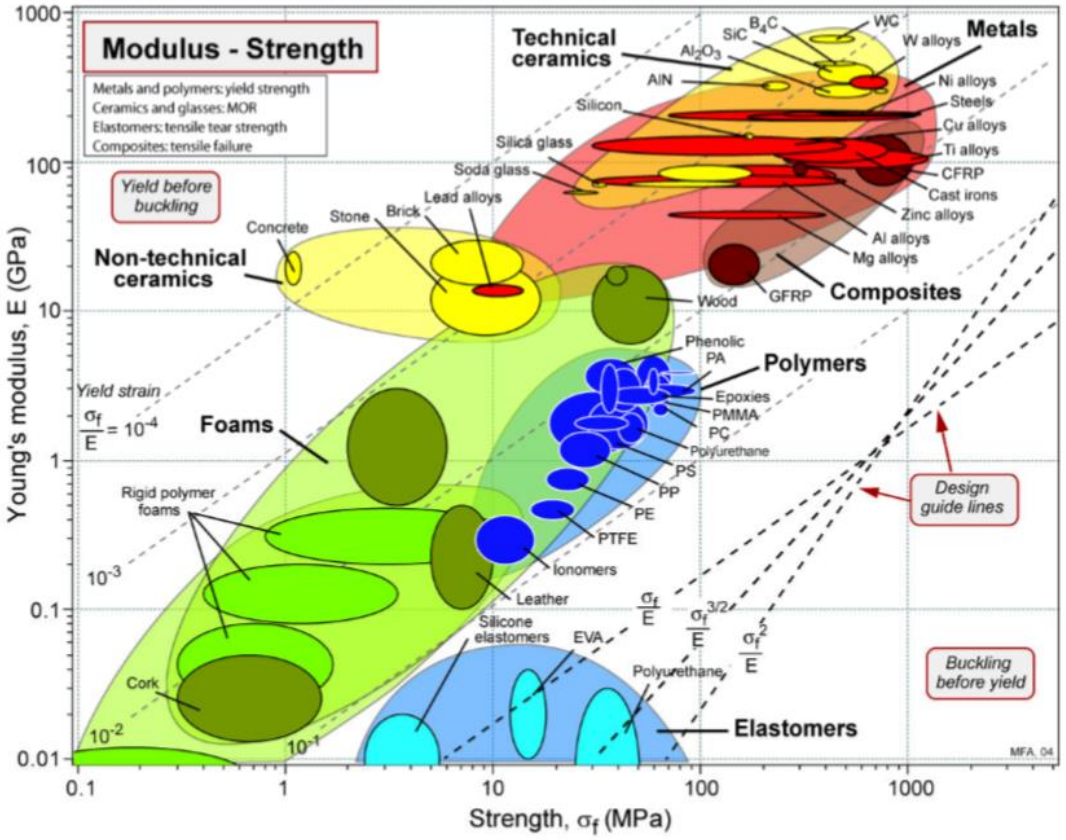

Figure 1. *Chart describes stiffness and strength. Corrosion resistant and cost-effective choices were selected from the both sides of the GFRP. It was not known the most optimal stiffness-strength –correlation. Steels have the highest strength but they are not automatically corrosion resistant. There are although a lot different coatings and surface modifications options. Steels and aluminum alloys have a wide range in strength and in aluminum selection aim was to find optimal relation between corrosion resistance and strength because they have a partial exclusivity. (42)*

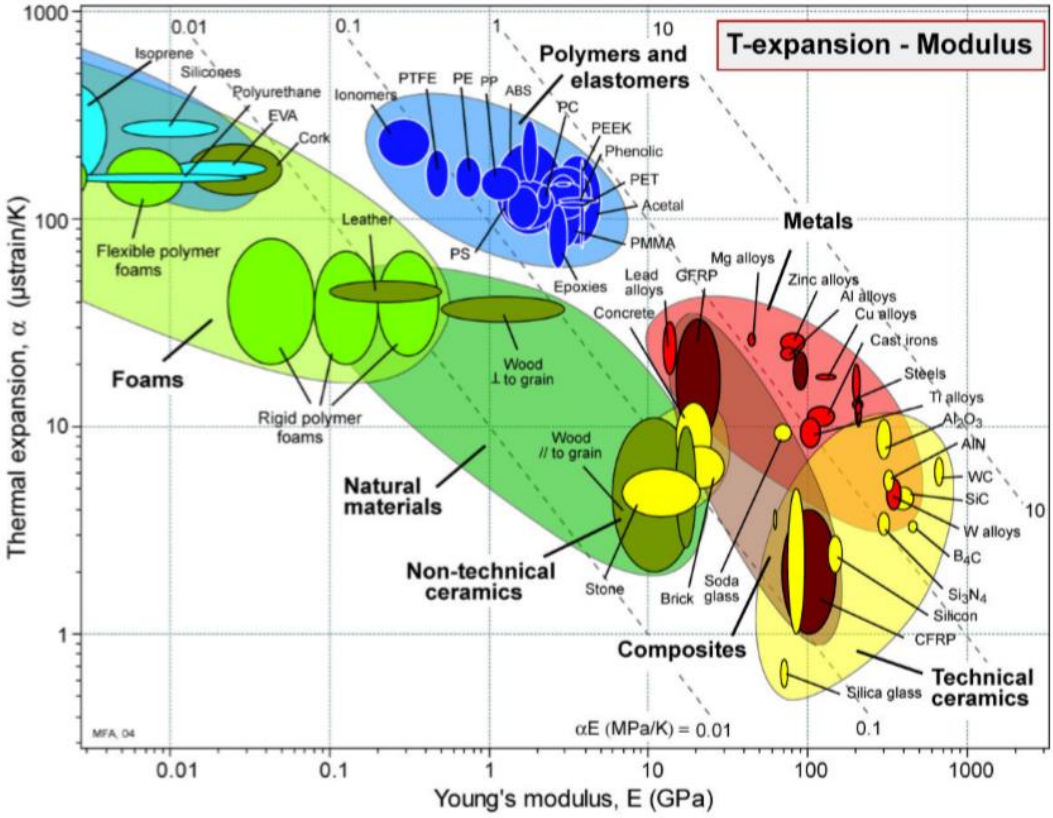

Figure 2. *Chart describes the relation between thermal expansion and stiffness. There were selected materials with lower and higher thermal expansion coefficient than GFRP's. PE and ABS were noticed to have significantly higher thermal expansion coefficients than GFRP but they were interesting options from other point of views. In addition, the range of GFRP's thermal expansion is wide according to chart and was unpredictable before testing. (42)*

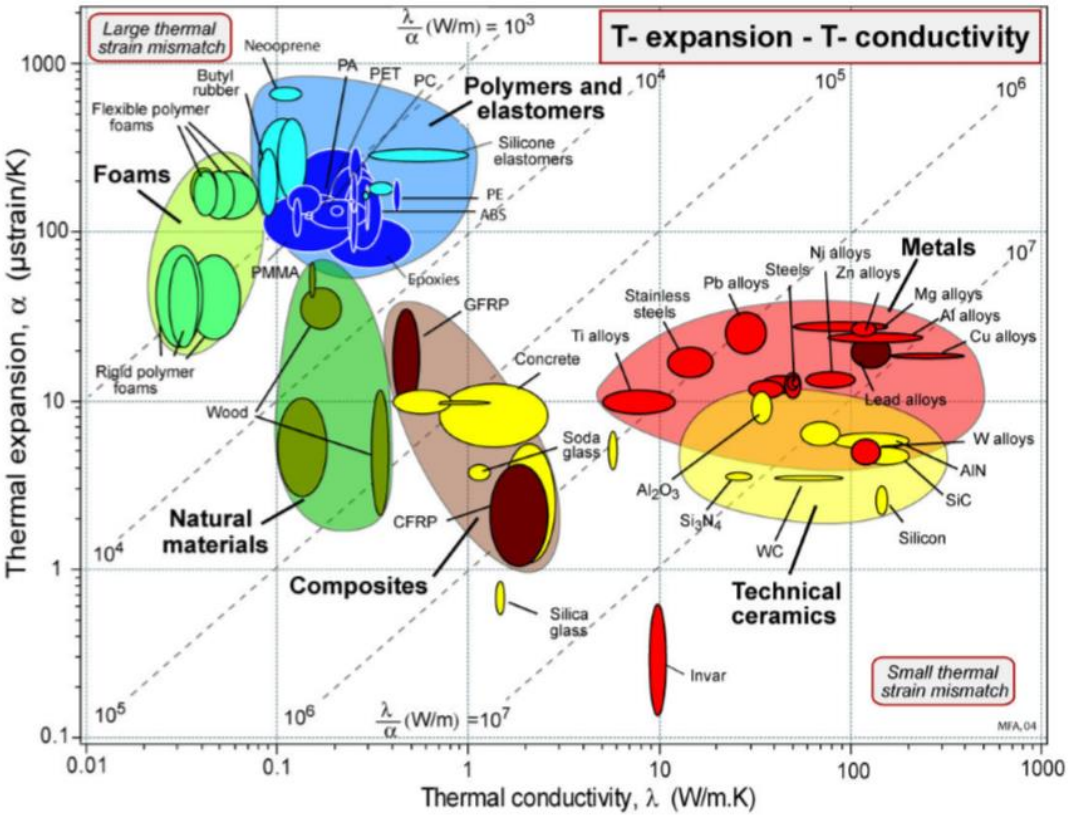

Figure 3. *Relation between thermal expansion and conductivity. In the progress of research, it came out that high thermal conductivity is beneficial to prevent ice forming in defrost process. GFRP has poor thermal conductivity compared to steels' and aluminum alloys' one. PE and ABS are in the same level with GFRP at the thermal conductivity. (42)*

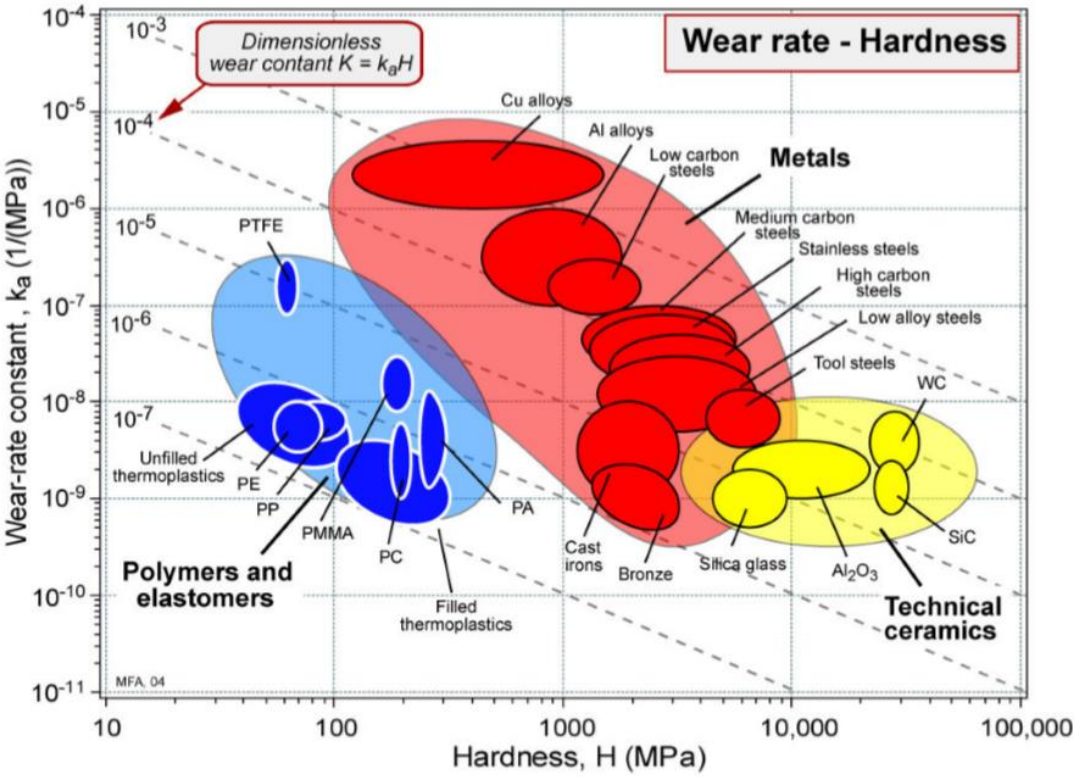

Figure 4. *Chart shows the relation between wear and hardness. Composites are not in the chart so there is no reference. Generally speaking: the higher the hardness the higher is the wear-rate constant. Polymers have advantage in wearing and metals in hardness. (42)*

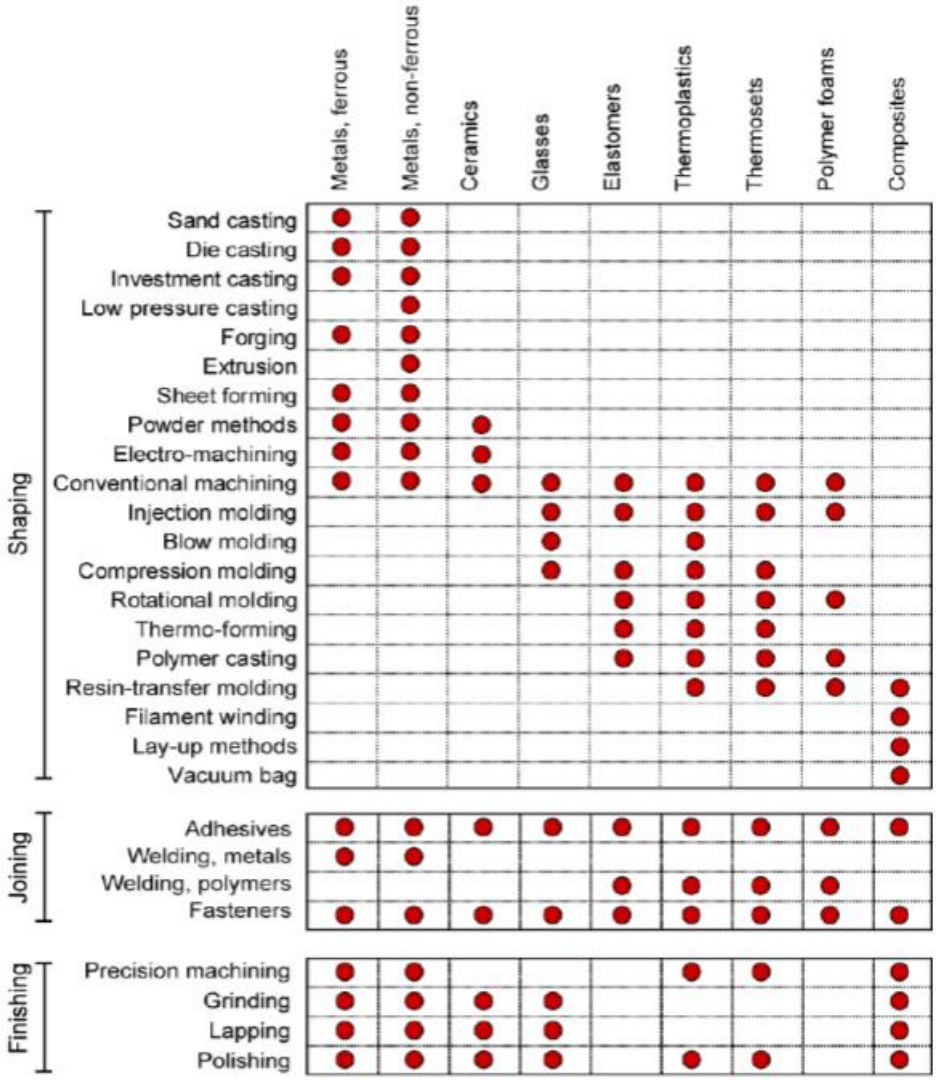

Figure 5. *Shaping, joining and finishing opportunities for different material groups. (42)*

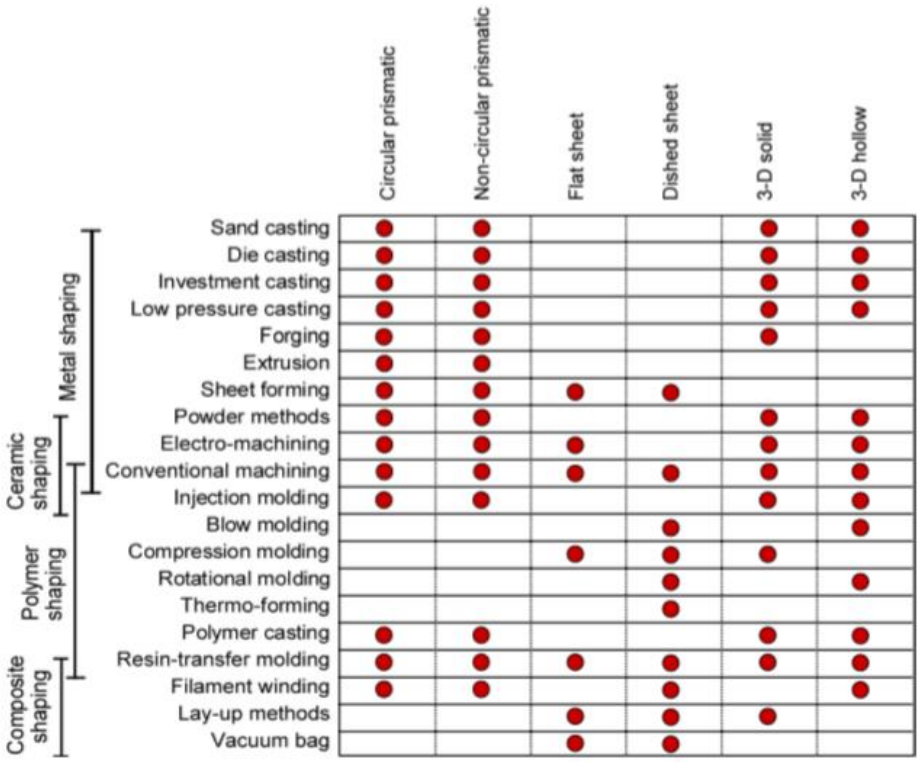

Figure 6. *Shape opportunities for different materials. (42)*

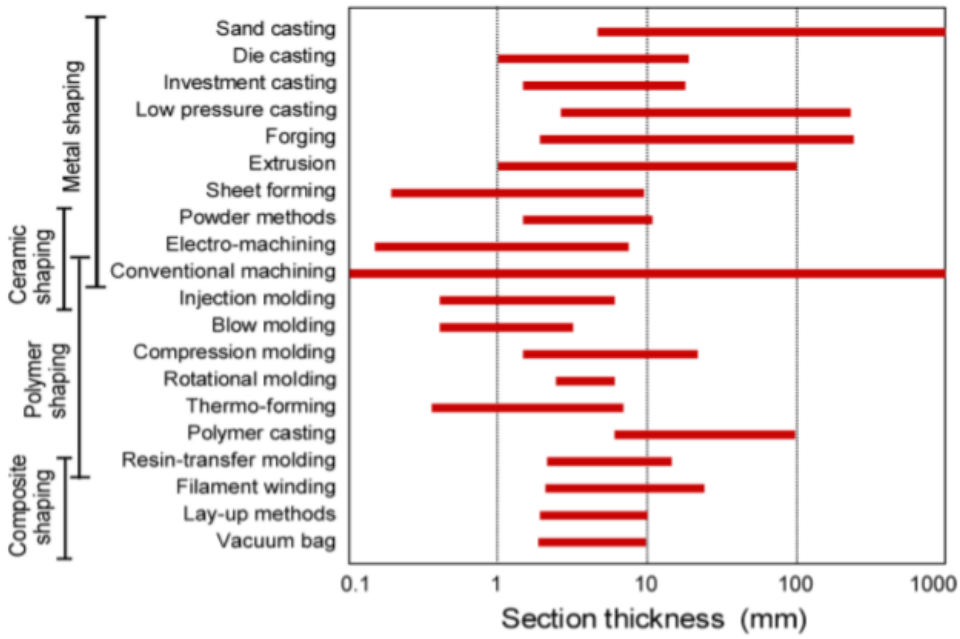

Figure 7. *Possible thickness range for material groups with different methods. (42)*

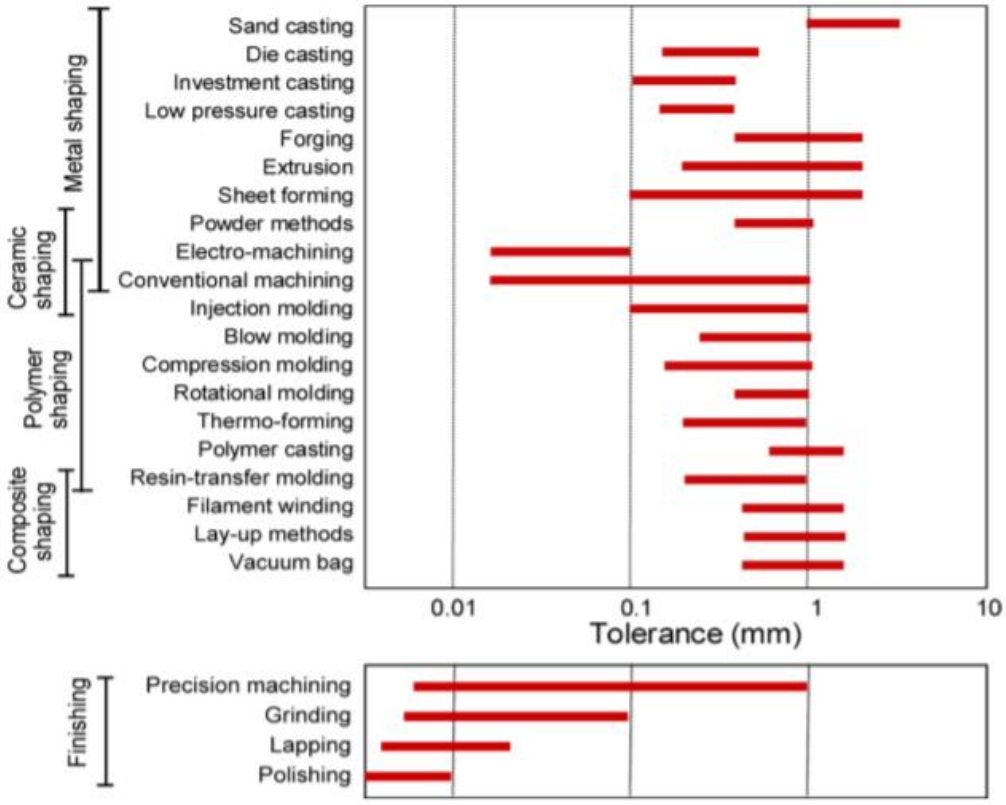

Figure 8. *Tolerance ranges for materials groups with different shaping methods. (42)*